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NSWCCD-50-TR--2002/064 OCTOBER 2002

HYDROMECHANICS DIRECTORATE REPORT

MEASUREMENT UNCERTAINTY ANALYSIS OF SHIP MODEL RESISTANCE AND SELF PROPULSION TESTS

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	Oct 2002	

4. TITLE AND SUBTITLE
MEASUREMENT UNCERTAINTY ANALYSIS OF SHIP MODEL RESISTANCE AND SELF PROPULSION TESTS

5. FUNDING NUMBERS
4-5000-001

6. AUTHOR(S)
Kenneth M. Forgach

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
David Taylor Model Basin,
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9500 MacArthur Blvd.
West Bethesda, MD 20817-5700

8. PERFORMING ORGANIZATION REPORT NUMBER
NSWCCD-50-TR--2002/064

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
David Taylor Model Basin,
NSWC, CARDEROCKDIV, Code 5200
9500 MacArthur Blvd.
West Bethesda, MD 20817-5700

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for Public Release. Distribution Unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This report presents a method for analyzing the uncertainties in the experimental measurements and results of ship model resistance and self propulsion tests. The method has been applied to the data from experiments with DTMB Model 5326-2. Sample calculations provide an outline or standard that may be applied to future experiments.

14. SUBJECT TERMS
Uncertainty Analysis, Measurement Accuracy, Bias, Precision

15. NUMBER OF PAGES
104

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	same as report

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

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U.S. CUSTOMARY AND METRIC EQUIVALENTS

U.S. CUSTOMARY	METRIC
1 inch	25.400 millimeter [0.0254 m (meter)]
1 foot	0.3048 m (meter)
1 foot per second	0.3048 m/s (meter per second)
1 knot	0.5144 m/s (meter per second)
1 pound (force)	4.4480 N (newtons)
1 degree (angle)	0.01745 rad (radians)
1 horsepower	0.7457 kW (kilowatts)
1 long ton	1.016 tonnes, 1.016 metric tons, or 1016.0 kilograms
1 inch water (60°F)	248.8 pa (pascals)

NOTATION

The notation used in this document is consistent with the International Towing Tank Conference (ITTC) Symbols and Terminology List - Beta Version 1996.

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ABSTRACT

This report presents a method for analyzing the uncertainties in the experimental measurements and results of ship model resistance and self propulsion tests. The method has been applied to the data from experiments with DTMB Model 5326-2. Sample calculations provide an outline or standard that may be applied to future experiments.

ADMINISTRATIVE INFORMATION

The report was written at the David Taylor Model Basin, Naval Surface Warfare Center, Carderock Division (NSWCCD), herein referred to as DTMB, by the Hydromechanics Directorate, Code 5200, under work unit number 4-5000-001.

UNCERTAINTY ANALYSIS METHODOLOGY

MEASUREMENT ACCURACY

All measurements have some error associated with them even after all calibrations and corrections have been applied. Total measurement error, δ_i, is the difference between the measured value and the true value which is, by definition, unknown. δ_i is composed of two components: bias error, β, and precision error, ε_i :

$$\delta_i = \beta + \varepsilon_i$$

Bias error is characterized as a fixed or systematic error. Multiple measurements of the same system at the same test set point will have a constant bias error. Precision error, also known as random or repeatability error, is an indicator of the "scatter" in the data. This scatter, a function of the unsteadiness of the phenomenon being measured and the instability (voltage fluctuations, etc.) of test equipment, approaches a normal distribution as the data sample size increases. An accurate measurement is one with small bias and precision errors. Figure 1 is a schematic representation of total, bias and precision error.

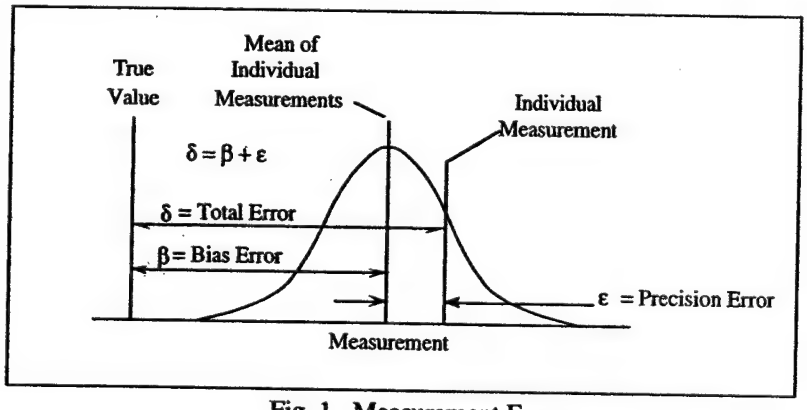

Fig. 1. Measurement Error

MEASUREMENT UNCERTAINTY

Because the true value of a variable remains unknown, the objective of uncertainty analysis then becomes to estimate reasonable limits for the bias and precision errors and to construct an uncertainty interval within which the true value of the measured variable can be expected to lie with a chosen level of confidence. For this analysis the 95% confidence level is appropriate. A valid statement about the value of the variable X based on experimental measurements (X_{meas}) would then be that "we are 95% confident that the true value of X lies within the interval [$X_{meas} \pm U_X$]". Where U_X, the overall uncertainty in the measured variable, represents the root-sum-square (RSS) combination of the bias error limit, B, and the precision error limit, P_X:

$$U_X = \sqrt{B^2 + P_X^2}$$

B often consists of several elemental error limits, all of which are estimated to the 95% confidence level and combined using RSS:

$$B = \sqrt{\sum_{k=1}^{M} B_k^2}$$

When possible, the value of P_X is determined directly from repeated test measurements :

$$P_X = t\, S_X.$$

Where S_X is the sample standard deviation or precision index and t is taken from the Student's t-Distribution Table with N-1 degrees of freedom at the 95% confidence level. A minimum sample size of N = 10 is reasonable for this analysis. When an adequate number of repeat measurements is not possible, P_X must be estimated based on past experience, manufacturer's equipment specifications or auxiliary tests.

PROPAGATION OF ERRORS INTO THE EXPERIMENTAL RESULT

All elemental bias and precision error limits are determined and combined, as above, to obtain the bias and precision error limits for each of the measured variables. These individual measurement error limits are then propagated through the uncertainty analysis expression to obtain the bias and precision limits for the experimental result. If the calculated result, r, is represented by the expression:

$$r = r\,(a, b, \ldots, z)$$

then the bias limit, B_r, and precision limit, P_r, for the result are found with the uncertainty analysis expression:

$$B_r = \left[\left(\frac{\partial r}{\partial a} B_a \right)^2 + \left(\frac{\partial r}{\partial b} B_b \right)^2 + \ldots + \left(\frac{\partial r}{\partial z} B_z \right)^2 \right]^{1/2}$$

$$P_r = \left[\left(\frac{\partial r}{\partial a} P_a \right)^2 + \left(\frac{\partial r}{\partial b} P_b \right)^2 + \ldots + \left(\frac{\partial r}{\partial z} P_z \right)^2 \right]^{1/2}$$

The equation representing the result is assumed to be continuous with continuous derivatives in the domain of interest and the bias limits, $B_a \ldots B_z$, of the measured variables are assumed to be independent of each other.

When individual measurement bias limits are correlated (not independent), the uncertainty analysis expression for propagating these measurement bias limits into the result must account for the extent of correlation. The above bias limit equation has been simplified to illustrate the case in which there are two correlated bias limits:

$$B_r = \left[\left(\frac{\partial r}{\partial a} B_a \right)^2 + \left(\frac{\partial r}{\partial b} B_b \right)^2 + 2 \frac{\partial r}{\partial a} \frac{\partial r}{\partial b} B'_a B'_b \right]^{1/2}$$

Where B'_a and B'_b denote that part of B_a and B_b that can be traced to identical error sources. One pertinent example of correlated bias is that which occurs when two different transducers have been calibrated against the same calibration standard.

Finally, the bias and precision limits for the result are then combined using RSS (for 95% coverage) to obtain the overall uncertainty in the result:

$$U_r = \sqrt{B_r^2 + P_r^2}$$

The methods outlined above and employed in the following analysis are developed in more detail by Coleman and Steele[1].

[1] Experimentation and Uncertainty Analysis for Engineers. Hugh W. Coleman and W. Glenn Steele, Jr. Copyright 1989, John Wiley & Sons, Inc.

ANALYSIS OF THE RESISTANCE TEST

During the resistance test, model speed and total resistance are measured for a range of speeds. At each speed in the range, several data "spots" are collected. The measured model speed, V, and resistance, R_T, for each spot represents the mean value of 2000 discrete samples collected over a 5 second sample period at a rate of 400 samples per second. Table A1 of Appendix A contains data from a resistance (PE) experiment with DTMB Model 5326-2. Spot number 85 from Table A1 is used in the sample calculations that follow.

MODEL SPEED (V)

Model Speed, V, through the water is equal to the speed of the towing carriage. For this sample calculation, V = 6.681 ft/sec. This speed is determined by counting the number of voltage pulses originating in a magnetic pickup. The stationary magnetic pickup senses the teeth on a large gear that is attached to and rotates with one of the carriage wheels. Each tooth encounter produces one voltage pulse (square wave). The gear has 520 teeth. The diameter, D, of the carriage drive wheel is known through direct measurement and the wheel circumference, C, is equal to π D. In the instant that data collection begins, the pulse counter is initiated. However, the counter's internal clock (time base) does not mark time until the first gear tooth is encountered. Counter time ends as the last gear tooth (within the 5 second sampling period) is encountered. Total counter time, t, is thereby associated with the correct integer number of pulses. Total counter time, t, varies with pulse frequency and is, in general, different by milliseconds than the 5 second data sampling period. During the time period, t, the total number of voltage pulses, n, is summed by the pulse counter and entered into the computer as pulse frequency, f = n/t. Model speed is then calculated:

$$V = \frac{(n/520)\pi D}{t} \quad \text{or} \quad V = \frac{f\pi D}{520}$$

The measured quantities required for the calculated value of model speed are the diameter of the carriage wheel, D, and the pulse frequency, f.

Model Speed Bias Limit (B_V).

Two elemental bias errors are associated with Model speed:

1. B_D: Wheel Diameter Bias Limit.

Wheel diameter is measured with a 20 inch micrometer to be 19.863 inches (1.655 ft). The estimated bias limit of 0.005 inches (0.00042 ft) accounts for measurement bias and possible variation in wheel diameter.

$$B_D = 0.005 \text{ inches} = 0.00042 \text{ ft.}$$

2. B_f: Pulse Frequency Bias Limit:

Manufacturer's specifications state that the accuracy of the pulse counter in determining frequency is:

$$\text{Accuracy} = \pm \text{ resolution} \pm \text{f (time base error)} = \pm 0.0096 \text{ pulses/second}$$

Where resolution = ± LSD ± 1.4 f (trigger error/gate time)
LSD = least significant digit = 0.0001 pulses/second
f = nominal frequency (@ V=6.681 ft/sec) = 668.1 pulses/second
trigger error = 0.000015 sec
gate time (nominal) = 5 sec
time base error = 0.00001

This specified accuracy refers to the bias limit inherent in the pulse counter itself and is therefore a zeroth-order bias limit estimate. As the magnetic pickup lag time error is negligible and since the frequency value is passed directly to the computer without analog to digital conversion, this accuracy can be related to the complete pickup/counter measuring system and is therefore a good estimate of the zeroth-order bias limit for pulse frequency.

$$B_{f,0} = 0.0096 \text{ pulses/second}$$

The elemental measurement bias limits are now propagated through the uncertainty analysis expression to obtain the bias limit for model speed, V.

$$B_V = \left[\left(\frac{\partial V}{\partial D} B_D\right)^2 + \left(\frac{\partial V}{\partial f} B_f\right)^2\right]^{1/2}$$

The required partial derivatives are obtained from the original equation for speed:

$$\frac{\partial V}{\partial D} = \frac{\pi f}{520} \quad \text{and} \quad \frac{\partial V}{\partial f} = \frac{\pi D}{520}$$

Substituting the previously estimated bias limits and the nominal values for the test variables we obtain:

$$B_V = \left[(4.04 \times 0.00042)^2 + (0.01 \times 0.0096)^2\right]^{1/2} = \pm 0.0017 \text{ ft/sec}$$

Model Speed Precision Limit (P_V).

More significant, however, is the precision limit for model speed, P_V. A first-order precision limit may be estimated by analyzing the data from a single experiment. This first-order precision limit estimate includes zeroth-order pulse counter precision effects within it as well as the actual unsteadiness of the towing carriage as it travels along the towing basin once it has reached "constant" speed.

Three speeds in the test range were chosen to represent a slow, medium and high ship speed: 13, 17 and 20 knots. For each of these three speeds at least twenty data spots were collected. A sample size of ten is, however, a reasonable minimum because the Student's t-value for N-1 = 9 degrees of freedom is equal to 2.26. For each of these three speeds, the standard deviation and the precision limit of the individual speed measurements about the mean speed is computed. Tables A2 through A4 show that for the three test speeds P_V is calculated to be: ± 0.0026 ft/s at 13 knots, ± 0.0046 ft/s at 17 knots and ± 0.0046 ft/s at 20 knots. These three values of P_V are plotted and fit with a curve in Figure A1. Values for the model speed precision limit, P_V, are now determined from the curve fit for any speed of interest. In this way a reasonable estimate of the variable precision limit can be obtained for the entire speed range based on limited data. Table A5 presents the values of P_V determined in this way. This is a first-order precision limit reflecting the scatter in a data set that was collected over a relatively short time span (a single experiment or set of "back-to-back" experiments) with the identical model and instrumentation.

For the sample calculation where measured V = 6.681 ft/s (Table A1 data spot number 85)

$$P_V = \pm 0.0049 \text{ ft/s}$$

Model Speed Overall Uncertainty (U_V).

Finally, the model speed bias and precision limits are combined using RSS (for 95% coverage) to obtain the overall uncertainty, U_V. For the sample calculation:

$$U_V = \left[(B_V)^2 + (P_V)^2\right]^{1/2} = \left[(0.0017)^2 + (.0049)^2\right]^{1/2} = \pm 0.0052 \text{ ft/sec}$$

Or, the true speed of Towing Carriage 1 during the time that this data spot was collected was 6.681 ft/sec ± 0.0052 ft/sec (± 0.08%) with 95% confidence. The most significant contributor to this overall uncertainty is the first-order precision limit for model speed (P_V = 0.0049 ft/s), which directly reflects the actual variation in Towing Carriage speed during the data collection.

Table A6 presents the uncertainty analysis of model speed for all the individual data spots collected during the resistance test. Table 1 is a summary of this model speed uncertainty analysis at interpolated whole knot (ship scale) increments.

MODEL TOTAL RESISTANCE (R_T)

The total resistance of the ship model, R_T, is measured with a calibrated variable reluctance transducer located within a DTMB block gage. The top of the block gage is attached to a towing post that is mounted to the towing carriage. The bottom of the block gage is attached to a gimbal that is mounted in the model. The tow bracket allows the block gage to heave with the model. The gimbal is located at the model waterline and as far forward in the model as practicable. A bracket also holds the stern of the model. This towing hardware leaves the model free to heave, pitch and roll, but restrains it in surge, sway and yaw. Transducer excitation originates in the Validyne High Gain Output Carrier Demodulator. Block gage output millivoltage is filtered and amplified by the Validyne that outputs ± 10 volts DC. The signal is further conditioned by an Ectron filter and passed to the analog to digital converter (A/D) where it is digitized and then entered into the computer program for further analysis. For this sample calculation, R_T = 16.469 lbf (Table A1, data spot 85).

Total Resistance Bias Limit (B_{RT}).

Six elemental bias errors associated with the measured value of R_T are identified:

1. B_{STD}: The bias error in the calibration standard.

During calibration the block gage is attached to a calibration stand in the same horizontal orientation as it will be during the test. A weight pan is attached to the block gage with a wire cable led over a pulley. Known weights, simulating the drag force, are applied incrementally to the weight pan and then removed in reverse order. This calibration cycle, adding and removing weights, is usually repeated at least twice. National Institute of Standards and Technology (NIST) Class F weights are used. Each individual weight (W_i) has a specified bias error of ± 0.01 % ($B_{Wi} = 0.0001 W_i$). The total weight, W_{STD}, applied at any time during the calibration is equal to the sum of the individual weights:

$$W_{STD} = W_1 + W_2 + \ldots + W_k = \sum_{i=1}^{k} W_i$$

For this sample calibration, the block gage was calibrated in the range 0 lbf to 35 lbf, in 5 lbf increments. The bias limit obtained from this expression is:

$$B_{STD} = \left[\left(\frac{\partial W_{STD}}{\partial W_1} B_{W_1} \right)^2 + \left(\frac{\partial W_{STD}}{\partial W_2} B_{W_2} \right)^2 + \ldots + \left(\frac{\partial W_{STD}}{\partial W_k} B_{W_k} \right)^2 \right]^{1/2} = \left[\sum_{i=1}^{k} B_{W_i}^2 \right]^{1/2}$$

Because

$$\frac{\partial W_{STD}}{\partial W_1} = \frac{\partial W_{STD}}{\partial W_2} = \ldots = \frac{\partial W_{STD}}{\partial W_k} = \frac{\partial W_{STD}}{\partial W_i} = 1$$

The bias limit, B_{STD}, is, then, a variable quantity equal to the square root of the sum of the squares of the biases of the individual weights on the calibration stand at any time:

$$B_{STD} = 0.0001 \left[\sum_{i=1}^{k} \left(W_i^2 \right) \right]^{1/2}$$

In order to apply this function to the analysis of the resistance test it is necessary to restate it in terms of measured model resistance, R_T, and convenient to approximate it with a curve fit. For this sample calculation, where $R_T = 16.469$ lbf,

$$B_{STD} = 0.0009 \text{ lbf}$$

Detailed calculations of B_{STD} are presented in Table B1 and Figure B1.

2. B_{cf}: The bias associated with using the block gage calibration curve fit equation .

As each weight is added to or removed from the calibration stand, as described above, one calibration data spot is recorded. The total weight applied for each spot, F_i, is known and entered into the calibration program. The output voltage, E_i, from the block gage / Validyne is read by a voltmeter and passed to the calibration program. For each calibration data spot an intermediate calibration constant, C_i, is calculated:

$$C_i = F_i / E_i \qquad \text{(lbf / volt)}$$

The final calibration constant, C, used during the resistance experiment is the mean of the intermediate constants:

$$C = \frac{1}{N} \sum_{i=1}^{N} C_i$$

Alternately, the calibration data may be fit with a linear least squares curve to establish the calibration constant. Because transducer response is extremely linear (correlation coefficient

typically equal to 0.999999) either of these two alternate values of the calibration constant is acceptable.

The standard error of estimate (SEE), a measure of the extent of scatter in the calibration data about the curve fit, is calculated :

$$SEE = \left\{ \frac{\sum_{i=1}^{N} [F_i - (C \times E_i)]^2}{N - 2} \right\}^{1/2} = 0.0275 \text{ lbf}$$

The error represented by this uncertainty interval represents the precision errors involved in the calibration process and the nonlinearity of the calibration curve. However, individual random effects become fossilized in the calibration equation and the bias limit, B_{cf}, that is brought into the ship model resistance test.

$$B_{cf} = 2SEE = 0.055 \text{ lbf}$$

The detailed calculations of SEE and B_{cf} are presented in Table B2.

3. B_E: The bias error introduced by the calibration voltmeter.

During calibration a voltmeter is substituted for the analog-to-digital converter (A/D) that is used during the resistance test data collection. Because of this and since voltmeter bias is not accounted for in B_{cf} above, it is included here as a separate item. Voltmeter accuracy as stated by the manufacturer is:

$$\text{Accuracy} = \pm (0.002\% \text{ of input} + 9 \times \text{resolution}) \text{ volts}$$

The voltmeter bias limit is estimated at the maximum voltage measured during the calibration, 5.0 volts corresponding to 35 lbf:

$$B_E = 0.00002 \text{ (5.0 volts)} + 9 \text{ (0.000010 volts)} = 0.00019 \text{ volts}$$

Or, applying the calibration constant:

$$B_E = 0.00019 \text{ V} \times 6.8362 \text{ lbf/V} = 0.0013 \text{ lbf}$$

4. B_{data}: The bias errors inherent in data acquisition instrumentation not accounted for in the calibration.

The most significant source of bias error introduced by instrumentation during data acquisition is that due to the analog-to-digital converter (A/D). Recall that because a voltmeter is substituted for the A/D during the block gage calibration this significant source of error is not accounted for in B_{cf} or B_E above.

The manufacturer's specifications state that the A/D has a full scale reading of 10 volts, a resolution of 14 binary bits (and sign), and an accuracy of ± 3 1/2 LSB (least significant bit) in the multiplexing mode. The bias error associated with the digitization of the analog voltage is then:

$$B_{dig} = 3\ 1/2 \left(\frac{10V}{2^{14}} \right) = 0.0021 \ \text{Volts}$$

Additional errors include the A/D bias errors due to nonlinearity (0.0001 V) and offset (0.0001 V) as well as the bias introduced by the use of an additional Ectron filter and intermediate wiring not present during calibration (0.0002 V). The total bias limit associated with data acquisition is then:

$$B_{data} = \left[0.0021^2 + 0.0001^2 + 0.0001^2 + 0.0002^2 \right]^{1/2} = 0.0021 \ \text{V}$$

Or, applying the calibration constant:

$$B_{data} = 0.0021 \ \text{V} \times 6.8362 \ \text{lbf/V} = 0.014 \ \text{lbf}$$

5. $B_{install}$: Block gage installation bias .

The block gage is a cube each side of which is 4 inches in length. The maximum misalignment between the orientation of the block gage as it is installed on the towing carriage and its orientation during calibration is estimated to be ± 0.035 inches in 4 inches or ± 0.50°. For small angles, the error in the force measurement is proportional to the cosine of the misalignment angle. For this sample calculation where R_T = 16.469 lbf, the 0.50° misalignment will result in a maximum force measurement error of 0.0006 lbf.

$$B_{install} = R_T - (\cos 0.5° * R_T) = 0.0006 \ \text{lbf}$$

6. $B_{concept}$: Conceptual bias errors :

Conceptual bias errors are those introduced due to inadequate design of the experiment or through necessary simplification of experiment design. Does the measurement really represent what is intended? Though no significant sources of conceptual bias have been identified, this item is included here.

$$B_{concept} = 0.0$$

These elemental bias error limits are combined to obtain the first order bias limit for the measurement of total resistance.

$$B_{R_T} = \left[B_{STD}^2 + B_{cf}^2 + B_E^2 + B_{data}^2 + B_{install}^2 + B_{concept}^2 \right]^{1/2}$$

$$B_{R_T} = \left[0.0009^2 + 0.055^2 + 0.0013^2 + 0.014^2 + 0.0006^2 + 0.0^2 \right]^{1/2} = \pm 0.057 \text{ lbf}$$

Total Resistance Precision Limit (P_{RT}).

The precision limit for model total resistance, P_{R_T}, is determined with the same method as that detailed above for the model speed precision limit. Tables A2 through A4 show that P_{R_T} is calculated to be ± 0.200 lbf at 13 knots, ± 0.254 lbf at 17 knots and ± 0.276 lbf at 20 knots. These three values of P_{R_T} are plotted and curve fit in Figure A2. Values for the model total resistance precision limit, P_{R_T}, may now be determined from the curve for any value of total resistance, R_T. Table A7 presents the values of P_{Rt} determined in this way. For this sample calculation, where measured R_T = 16.469 lbf (Table A1, data spot number 85) :

$$P_{R_T} = \pm 0.280 \text{ lbf}$$

This is a first-order precision limit reflecting the scatter in a data set that was collected over a relatively short time span (a single experiment or set of "back-to-back" experiments) with the identical model and instrumentation.

Total Resistance Overall Uncertainty (U_{RT}).

The bias and precision error limits are now combined using RSS (for 95% coverage) to obtain the overall uncertainty, U_{RT}. For the sample calculation:

$$U_{R_T} = \left[\left(B_{R_T} \right)^2 + \left(P_{R_T} \right)^2 \right]^{1/2} = \left[(0.057)^2 + (0.280)^2 \right]^{1/2} = \pm 0.286 \text{ lbf}$$

Or, we are 95% confident that the true value of model total resistance measured for the data spot is within ±0.286 lbf of the reported 16.469 lbf (± 1.74%). As with model speed, the most significant contributor to this overall uncertainty is the precision limit.

Table A8 presents the uncertainty analysis of model total resistance for all the individual data spots collected during the resistance test. Table 2 is a summary of the total resistance uncertainty analysis at interpolated whole knot (ship scale) increments.

OVERALL UNCERTAINTY IN THE RESULT (U_{CT}).

Elemental bias and precision error limits were determined and combined, above, to obtain the bias and precision error limits for each of the measured variables. Now these individual measurement error limits are propagated through the uncertainty analysis expression to obtain the bias and precision limits and overall uncertainty for the experimental result.

The non-dimensional Coefficient of Total Resistance, C_T, is one format for expressing the results of the resistance test. For the sample calculation:

$$C_T = \frac{R_T}{1/2\rho S V^2} = 3.27E-3$$

Where	R_T	= Measured model total resistance	=	16.469 lbf
	ρ	= Density of tank water	=	1.9365 lbf-s^2 / ft^4
	S	= Model wetted surface	=	116.7 ft^2
	V	= Measured model speed	=	6.681 ft / s

Bias and precision error limits for model total resistance, R_T, and model speed, V, were determined above. Error limits still need to be established of the two remaining variables, ρ and S.

For this analysis, there is assumed to be no uncertainty in the stated value for model wetted surface, S.

Water density is not measured directly. Rather, water temperature is measured and the corresponding density is read from a table (American Towing Tank Conference, 1942). To establish the bias and precision limits for water density, ρ, we look at the bias and precision with which the tank water temperature is measured and the bias inherent in the tabulated property value of ρ.

Thermometer bias is equivalent to the manufacturer's stated accuracy: ± 0.5° F. The precision error in reading the thermometer is estimated also to be equal to ± 0.5° F. Total uncertainty in water temperature is equal to:

$$U_T = \left[B_T^2 + P_T^2\right]^{1/2} = \left[0.5^2 + 0.5^2\right]^{1/2} = \pm 0.71^{\circ}F$$

This level of uncertainty in temperature measurement accounts for the following bias when consulting the property table for density: ± 0.0003 lbf s^2 / ft^4 . Consider also the uncertainty for the bias inherent in the tabulated values (estimated at ± 0.25% = ± 0.005 lbf s^2 / ft^4) and the uncertainty in the actual composition of the tank water (estimated at ± 0.25% = ± 0.005 lbf s^2 / ft^4). Combine these to determine the bias limit for water density, B_ρ:

$$B_\rho = \left[0.0003^2 + 0.005^2 + 0.005^2\right]^{1/2} = \pm\ 0.007 \text{ lbf s}^2/\text{ft}^4$$

The first order bias and precision limits for the Coefficient of Total Resistance, C_T, are calculated:

$$B_{C_T} = \left[\left(\frac{\partial C_T}{\partial R_T} B_{R_T}\right)^2 + \left(\frac{\partial C_T}{\partial \rho} B_\rho\right)^2 + \left(\frac{\partial C_T}{\partial V} B_V\right)^2\right]^{1/2}$$

$$P_{C_T} = \left[\left(\frac{\partial C_T}{\partial R_T} P_{R_T}\right)^2 + \left(\frac{\partial C_T}{\partial V} P_V\right)^2\right]^{1/2}$$

The required partial derivatives are obtained from the original equation for C_T:

$$\frac{\partial C_T}{\partial R_T} = \frac{2}{S\rho V^2} \quad , \quad \frac{\partial C_T}{\partial \rho} = \frac{-2R_T}{S\rho^2 V^2} \quad \text{and} \quad \frac{\partial C_T}{\partial V} = \frac{-4R_T}{S\rho V^3}$$

Substituting the previously estimated bias and precision limits and the nominal values for the test variables we obtain:

$$B_{C_T} = [(0.0002 * 0.057)^2 + (-0.0017 * 0.007)^2 + (-0.0010 * 0.0017)^2]^{1/2} = \pm\ 1.66\text{ E-5}$$

$$P_{C_T} = [(0.0002 * 0.280)^2 + (-0.0010 * 0.0049)^2]^{1/2} = \pm\ 5.62\text{ E-5}$$

The overall uncertainty assigned to this particular value of total resistance coefficient is then:

$$U_{C_T} = \left[\left(B_{C_T}\right)^2 + \left(P_{C_T}\right)^2\right]^{1/2} = \left[\left(1.66\text{ E}-5\right)^2 + \left(5.62\text{ E}-5\right)^2\right]^{1/2} = \pm\ 5.86\text{ E}-5$$

Or, the true value for the Coefficient of Total Resistance for this sample data spot is 3.27 E-3 ±5.86 E-5 (±1.79 %) with 95% confidence. Table A9 presents the C_T uncertainty analysis for all the individual data spots collected during the resistance test. Table 3 is a summary of the C_T uncertainty analysis at interpolated whole knot (ship scale) increments.

ANALYSIS OF THE SELF PROPULSION TEST

During the model self propulsion test, the following model scale quantities are measured:

Model speed: V

Model tow force : Fd

Propeller shaft thrust: T

Propeller shaft torque: Q

Propeller shaft revolution rate: N

The data collection procedure used during the self propulsion test is similar to that used during the resistance test: at each speed in the range, several data "spots" are collected. Each spot represents the mean value of 2000 discrete samples collected over a 5 second sample period at a rate of 400 samples per second. Table A10 contains data from a self propulsion (PD) experiment with DTMB Model 5326-2. Data spot number 181 from Table A10 is used in the sample calculations that follow.

MODEL SPEED (V)

The measurement and analysis of model speed from the self propulsion test is identical to that of the resistance test. Refer to the previous section of this report for a detailed description of the method. A summary of the results of the sample calculation of the self propulsion test model speed uncertainty analysis follows:

Model speed =	V =	6.692 ft/sec (see Table A10, data spot 181)
Wheel Diameter Bias Limit =	B_D =	0.00042 ft
Pulse Frequency Bias Limit =	B_f =	0.0096 pulses/sec
Model Speed Bias Limit =	B_V =	0.0017 ft/sec
Model Speed Precision Limit =	P_V =	0.0030 ft/sec
Model Speed Overall Uncertainty =	U_V =	0.0034 ft/sec (0.05%)

Tables A11 through A14 and Figure A3 show the calculation of model speed precision limit. Table A15 presents the elemental bias errors and summarizes the model speed uncertainty analysis for all the individual data spots collected during the self propulsion test. Table 4 is a summary of the model speed uncertainty analysis at interpolated whole knot (ship scale) increments.

MODEL TOW FORCE (Fd)

In order to achieve equality between model and ship propeller efficiencies the model is assisted during the self propulsion experiment with the application of the correct amount of tow force. This tow force, Fd, is also known as the "overloaded ITTC loading". Because the ratio of viscous resistance to residuary resistance is larger for the model than for the ship at the same Froude scaled speed, a fully self propelled model would need to produce proportionally more propeller thrust than the full scale ship. The model propeller would be overloaded relative to the ship propeller. By

applying the correct amount of tow force to the model during the propulsion experiment, the model propeller works against an "ideal" resistance (R_I) which is less than the actual or total model resistance (R_T) by the amount Fd. This technique of propelling the model at the "ship self propulsion point" rather than at the "model self propulsion point" results in equality between the model and ship propeller thrust loading coefficient which is necessary for identical model and ship propeller efficiencies.

Self propulsion test model tow force is measured with a different DTRC block gage than that used during the resistance test described above and a separate calibration of this block gage is performed to cover the diminished range for Fd. During this test, Fd varied between 1.3 lbf and 5.0 lbf. However, the same six elemental bias error sources identified for the measurement of model total resistance, R_T, apply to the measurement of self propulsion tow force, Fd.

The measurement and analysis of model tow force from the self propulsion test is identical to that of the model total resistance. Refer to the previous section of this report for a detailed description of the method. A summary of the results of the sample calculation of the self propulsion test model tow force uncertainty analysis follows:

Model Tow Force =	Fd =	4.123 lbf (see Table A10, data spot 181)
Calibration Standard Bias Limit =	B_{STD} =	0.0002 lbf (see Table B3 & Fig. B2)
Calibration Curve Fit Bias Limit =	B_{cf} =	0.0055 lbf (see Table B4)
Calibration Voltmeter Bias Limit =	B_E =	0.0007 lbf
Data Acquisition Instrumentation Bias Limit =	B_{data} =	0.0140 lbf
Block Gage Installation Bias Limit =	$B_{install}$ =	0.0002 lbf
Exp. Conceptual Design Bias Limit	$B_{concept}$ =	0.0000 lbf
Tow Force Bias Limit	B_{Fd} =	0.015 lbf
Tow Force Precision Limit =	P_{Fd} =	0.125 lbf
Tow Force Overall Uncertainty =	U_{Fd} =	0.126 lbf (3.06%)

Tables A11 through A13, Table A16 and Figure A4 show the calculation of model tow force precision limit. Table A17 presents the elemental bias errors and summarizes the model tow force uncertainty analysis for all the individual data spots collected during the self propulsion test. Table 5 is a summary of the model tow force uncertainty analysis at interpolated whole knot (ship scale) increments.

MODEL PROPELLER SHAFT THRUST (T)

Model propeller shaft thrust, T, is measured with a 55 lbf (245 N) capacity Kempf and Remmers transmission dynamometer. The thrust transducer is a non-rotating full bridge strain gage type. The dynamometer is attached to a frame which is mounted to the inside bottom of the model. The frame allows for precise alignment of the dynamometer and the propeller shaft which are directly coupled to each other. Transducer excitation originates in the Vishay strain gage conditioning amplifier. Transducer output millivoltage is filtered and amplified by the Vishay which then outputs ± 10 volts DC. The signal is further conditioned by an Ectron filter and passed to the analog to digital converter (A/D) where it is digitized and then entered into the computer program for further analysis. For this sample calculation, T = 14.738 lbf (Table A10, data spot 181).

Thrust Bias Limit (B_T).

Six elemental bias errors associated with the measurement of T are identified:

1. B_{STD}: The bias error in the calibration standard.

The transmission dynamometer is calibrated for thrust on a fixture which employs a 3 to 1 lever arm. The simulated thrust force is therefore 3 times greater than the calibration standard weight applied. The total Thrust, T_{STD}, at any time during the calibration is equal to the sum of the products of the individual weights, W_i, and the 3 to 1 ratio, R, of the lever:

$$T_{STD} = (W_1 \times R) + (W_2 \times R) + \ldots + (W_k \times R) = \sum_{i=1}^{k} (W_i \times R)$$

The weights used are National Institute of Standards and Technology (NIST) Class F weights with a specified bias error, B_{W_i}, of ± 0.01 % .

If $R = \frac{L_1}{L_2} = \frac{7.5 \text{ in.}}{2.5 \text{ in.}} = \frac{3}{1}$, $\frac{\partial R}{\partial L_1} = \frac{1}{L_2} = \frac{1}{2.5 \text{ in}}$ and $\frac{\partial R}{\partial L_2} = -\frac{L_1}{L_2^2} = -\frac{7.5 \text{ in.}}{2.5^2 \text{ in.}^2}$

then the bias error, B_R, associated with the ratio is

$$B_R = \left[\left(\frac{\partial R}{\partial L_1} B_{L_1} \right)^2 + \left(\frac{\partial R}{\partial L_2} B_{L_2} \right)^2 \right]^{1/2} = 0.0063$$

for $B_{L_1} = B_{L_2} = \pm$ 0.005 inches.

The bias limit for the thrust calibration standard is then obtained from the following expression :

$$B_{STD} = \left[\left(\sum_{i=1}^{k} \left(\frac{\partial T_{STD}}{\partial W_i} B_{W_i} \right)^2 \right) + \left(\frac{\partial T_{STD}}{\partial R} B_R \right)^2 \right]^{1/2}$$

If $\frac{\partial T_{STD}}{\partial W_i} = R$, $\frac{\partial T_{STD}}{\partial R} = \sum_{i=1}^{k} W_i$ and B_{W_i} is variable and equal to 0.01 % of each of the individual weights, then the bias limit, B_{STD} is also variable:

$$B_{STD} = \left[\left((0.0001\ R)^2 \sum_{i=1}^{k} W_i^2 \right) + \left(0.0063 \sum_{i=1}^{k} W_i \right)^2 \right]^{1/2}$$

In order to apply this function to the analysis of the propulsion test it is necessary to restate it in terms of measured model propeller shaft thrust, T, and convenient to approximate it with a curve fit (see Table B5 and Figure B3) For this sample calculation, where T = 14.738 lbf,

$$B_{STD} = 0.0310 \text{ lbf}$$

2. B_{cf}: The bias associated with using the block gage calibration curve fit equation .

The standard error of estimate (SEE) and the calibration curvefit bias, B_{cf}, are calculated:

$$SEE = \left\{ \frac{\sum_{i=1}^{N} \left[F_i - (C \times E_i) \right]^2}{N-2} \right\}^{1/2} = 0.0172 \text{ lbf}$$

$$B_{cf} = 2SEE = 0.0344 \text{ lbf}$$

The thrust calibration data and detailed calculations for SEE and B_{cf} are presented in Table B6.

3. B_E: The bias error introduced by the calibration voltmeter.

Voltmeter accuracy as stated by the manufacturer is:

$$\text{Accuracy} = \pm (0.002\% \text{ of input} + 9 \times \text{resolution}) \text{ volts}$$

The voltmeter bias limit is estimated at the maximum voltage measured during the calibration, 6.6 volts corresponding to 36 lbf:

$$B_E = 0.00002\ (6.6 \text{ volts}) + 9\ (0.000010 \text{ volts}) = 0.00022 \text{ volts}$$

Or, applying the calibration constant:

$$B_E = 0.00022\ V \times 5.4067\ lbf/V = 0.0012\ lbf$$

4. B_{data}: The bias errors inherent in data acquisition instrumentation not accounted for in the calibration.

The most significant source of bias error introduced by instrumentation during data acquisition is that due to the analog-to-digital converter (A/D).

$$B_{dig} = 3\ 1/2 \left(\frac{10V}{2^{14}} \right) = 0.0021\ \ Volts$$

Additional errors include the A/D bias errors due to nonlinearity (0.0001 V) and offset (0.0001 V) as well as the bias introduced by the use of an additional Ectron filter and intermediate wiring not present during calibration (0.0002 V). The total bias limit associated with data acquisition is then:

$$B_{data} = \left[0.0021^2 + 0.0001^2 + 0.0001^2 + 0.0002^2 \right]^{1/2} = 0.0021\ V$$

Or, applying the calibration constant

$$B_{data} = 0.0021\ V \times 5.4067\ lbf/V = 0.0114\ lbf$$

5. $B_{install}$: Dynamometer installation bias .

The dynamometer mounting frame or bracket has a footprint that is approximately 4 inches wide by 15 inches long. The maximum misalignment between the orientation of the dynamometer as it is installed in the model and its orientation during calibration is estimated to be ± 0.035 inches in 15 inches or ± 0.13°. For small angles, the error in the thrust force measurement is proportional to the cosine of the misalignment angle. For this sample calculation where T = 14.738 lbf, the 0.13° misalignment will result in a maximum force measurement error of 0.00004 lbf.

$$B_{align} = T - (\cos 0.13° \times T) = 0.00004\ lbf$$

In addition, model propeller shaft bearings and seals also have an effect on the thrust (and torque - see the following discussion) measured at the dynamometer. Immediately before the self propulsion test begins, propeller shaft "no-loads" are collected to quantify and correct for these effects. A propeller "dummy hub", an accurately modeled propeller hub without blades, is installed on the shaft. The shaft is turned at several different rotation rates in the test range. At each of these RPMs, thrust is measured. For this case, no-loads were collected at 200 through 600 RPM, in 100 RPM increments. This array of thrust versus RPM is stored in the data collection program and accessed during the self propulsion test. For every self propulsion test data spot, the

appropriate no-load is correctly applied to the measured thrust. For this test, thrust no-loads varied between 0.001 lbf and 0.071 lbf. The average thrust no-load value of 0.041 lbf is used as a reasonable bias error due to possible errant variations in no-load:

$$B_{nl} = 0.041 \text{ lbf}$$

Combining these two, the total bias limit associated with dynamometer installation is then:

$$B_{install} = \left[B_{align}^2 + B_{nl}^2\right]^{1/2} = \left[0.00004^2 + 0.041^2\right]^{1/2} = 0.041 \text{ lbf}$$

6. $B_{concept}$: Conceptual bias errors :

No significant sources of conceptual bias have been identified:

$$B_{concept} = 0.0$$

These elemental bias error limits are combined to obtain the first order bias limit for the measurement of model propeller shaft thrust, B_T.

$$B_T = \left[B_{STD}^2 + B_{cf}^2 + B_E^2 + B_{data}^2 + B_{install}^2 + B_{concept}^2\right]^{1/2}$$

$$B_T = \left[0.0310^2 + 0.0344^2 + 0.0012^2 + 0.0114^2 + 0.0410^2 + 0.0000^2\right]^{1/2} = 0.063 \text{ lbf}$$

Thrust Precision Limit (P_T).

The precision limit for model propeller shaft thrust, P_T, is determined with the same method as that detailed above for the resistance test model speed precision limit. Tables A11 through A13 show that P_T is calculated to be ± 0.037 lbf at 13 knots, ± 0.081 lbf at 17 knots and ± 0.099 lbf at 20 knots. These three values of P_T are plotted and curve fit in Figure A5. Values for P_T may now be determined from the curve for any value of propeller shaft thrust, T. Table A18 presents the values of P_T determined in this way. For this sample calculation, where measured T = 14.738 lbf (Table A10, data spot 181):

$$P_T = \pm 0.103 \text{ lbf}$$

Thrust Overall Uncertainty (U_T).

The bias and precision error limits are now combined to obtain the overall uncertainty in the value of measured model propeller shaft thrust, U_T.

$$U_T = \left[B_T^2 + P_T^2\right]^{1/2} = \left[0.063^2 + 0.103^2\right]^{1/2} = \pm 0.121 \text{ lbf}$$

For this sample calculation in which T_m = 14.738 lbf, this represents an uncertainty of ± 0.82% with 95% confidence. Table A19 presents the uncertainty analysis of model propeller shaft thrust for all the individual data spots collected during the self propulsion test. Table 6 is a summary of the propeller shaft thrust uncertainty analysis at interpolated whole knot (ship scale) increments.

MODEL PROPELLER SHAFT TORQUE (Q)

Model propeller shaft torque, Q, is measured with the same transmission dynamometer described in the preceding section concerning propeller shaft thrust. The torque transducer is a rotating full bridge strain gage type with a capacity of 85 in-lbf (9.6 m-N). The torque transducer is connected to the terminals via hard-silver rings and carbon brushes. For this sample calculation, Q = 28.497 in-lbf (Table A10, data spot 181).

Torque Bias Limit (B_Q).

Six elemental bias errors associated with the measured value of Q are identified:

1. B_{STD}: The bias error in the calibration standard.

The transmission dynamometer is calibrated for torque on a fixture with a balanced 10 inch long moment arm. Calibration weights are applied to pans hung from the arm. The total Torque, Q_{STD}, applied at any time during the calibration is equal to the sum of the products of the individual weights, W_i, and the 10 inch moment arm, L:

$$Q_{STD} = (W_1 \times L) + (W_2 \times L) + \ldots + (W_k \times L) = \sum_{i=1}^{k} (W_i \times L)$$

The weights used are National Institute of Standards and Technology (NIST) Class F weights with a specified bias error, B_W, of ± 0.01 % . The bias error associated with the measured length of the moment arm on the calibration fixture, B_L, is estimated to be ± 0.005 inches in 10.00 inches.

The bias limit is obtained from the following expression :

$$B_{STD} = \left[\left(\sum_{i=1}^{k} \left(\frac{\partial Q_{STD}}{\partial W_i} B_{W_i} \right)^2 \right) + \left(\frac{\partial Q_{STD}}{\partial L} B_L \right)^2 \right]^{1/2}$$

If $\frac{\partial Q_{STD}}{\partial W_i} = L$, $\frac{\partial Q_{STD}}{\partial L} = \sum_{i=1}^{k} W_i$ and B_{W_i} is a variable quantity equal to 0.01 % of each of the individual weights, W_i, on the calibration fixture at any time, then the bias limit, B_{STD}, is also variable:

$$B_{STD} = \left[\left((0.0001\ L)^2 \sum_{i=1}^{k} W_i^2 \right) + \left(.005 \sum_{i=1}^{k} W_i \right)^2 \right]^{1/2}$$

In order to apply this function to the analysis of the propulsion test it is necessary to restate it in terms of measured model propeller shaft torque, Q, and convenient to approximate it with a curve fit (see Table B7 and Figure B4). For this sample calculation, where Q = 28.497 in-lbf:

$$B_{STD} = 0.0143 \text{ in-lbf}$$

2. B_{cf}: The bias associated with using the block gage calibration curve fit equation .

The standard error of estimate (SEE) and the calibration curvefit bias, B_{cf}, are calculated:

$$SEE = \left\{ \frac{\sum_{i=1}^{N} \left[M_i - (C \times E_i) \right]^2}{N-2} \right\}^{1/2} = 0.0417 \text{ in} - \text{lbf}$$

$$B_{cf} = 2SEE = 0.0834 \text{ in-lbf}$$

The torque calibration data and detailed calculations for SEE and B_{cf} are presented in Table B8.

3. B_E: The bias error introduced by the calibration voltmeter.

Voltmeter accuracy as stated by the manufacturer is:

$$\text{Accuracy} = \pm (0.002\% \text{ of input} + 9 \times \text{resolution}) \text{ volts}$$

The voltmeter bias limit is estimated at the maximum voltage measured during the calibration, 6.3 volts corresponding to 60 in-lbf:

$$B_E = 0.00002\ (6.3 \text{ volts}) + 9\ (0.000010 \text{ volts}) = 0.0002 \text{ volts}$$

Or, applying the calibration constant:

$$B_E = 0.0002 \text{ volts} \times 9.472 \text{ in-lbf/volt} = 0.0019 \text{ in-lbf}$$

4. B_{data}: The bias errors inherent in data acquisition instrumentation not accounted for in the calibration.

The most significant source of bias error introduced by instrumentation during data acquisition is that due to the analog-to-digital converter (A/D).

$$B_{dig} = 3\ 1/2\left(\frac{10V}{2^{14}}\right) = 0.0021 \text{ Volts}$$

Additional errors include the A/D bias errors due to nonlinearity (0.0001 V) and offset (0.0001 V) as well as the bias introduced by the use of an additional Ectron filter and intermediate wiring not present during calibration (0.0002 V). The total bias limit associated with data acquisition is then:

$$B_{data} = \left[0.0021^2 + 0.0001^2 + 0.0001^2 + 0.0002^2\right]^{1/2} = 0.0021 \text{ V}$$

Or, applying the calibration constant

$$B_{data} = 0.0021 \text{ volts x } 9.472 \text{ in-lbf/volt} = 0.0199 \text{ in-lbf}$$

5. $B_{install}$: Dynamometer installation bias .

Propeller torque is properly transmitted to the dynamometer even with some angular misalignment. The maximum misalignment between the shaft and the dynamometer was estimated to be ±0.13° (see the discussion above on thrust installation bias). This minor misalignment does not contribute to installation bias with respect to torque.

However, shaft bearings and seals do have an effect on the torque measurement. The technique of applying shaft "no-loads" in order to quantify and correct for these effects was described in the above discussion on dynamometer installation bias with respect to shaft thrust. For this test, torque no-loads varied between 0.007 in-lbf and 0.093 in-lbf within the range of 200 through 600 RPM. The average torque no-load value of 0.051 in-lbf is used as a reasonable bias error due to possible errant or non-repeating variations in no-load:

$$B_{install} = B_{nl} = 0.051 \text{ in-lbf}$$

6. $B_{concept}$: Conceptual bias errors :

No significant sources of conceptual bias have been identified:

$$B_{concept} = 0.0$$

These elemental bias error limits are combined to obtain the first order bias limit for the measurement of model propeller shaft torque, B_Q .

$$B_Q = \left[B_{STD}^2 + B_{cf}^2 + B_E^2 + B_{data}^2 + B_{install}^2 + B_{concept}^2\right]^{1/2}$$

$$B_Q = \left[0.0143^2 + 0.0834^2 + 0.0019^2 + 0.0199^2 + 0.0510^2 + 0.0000^2\right]^{1/2} = \pm 0.101 \text{ in} - \text{lbf}$$

Torque Precision Limit (P_Q).

The precision limit for model propeller shaft torque, P_Q, is determined with the same method as that detailed above for the resistance test model speed precision limit. Tables A11 through A13 show that P_Q is calculated to be ± 0.073 in-lbf at 13 knots, ± 0.116 in-lbf at 17 knots and ± 0.145 in-lbf at 20 knots. These three values of P_Q are plotted and curve fit in Figure A6. Values for P_Q may now be determined from the curve for any value of propeller shaft torque, Q. Table A20 presents the values of P_Q determined in this way. For this sample calculation, where measured Q = 28.497 in-lbf (Table A10, data spot 181):

$$P_Q = \pm 0.147 \text{ in-lbf}$$

Torque Overall Uncertainty (U_Q).

The bias and precision error limits are now combined to obtain the overall uncertainty in the value of measured model propeller shaft torque, U_Q.

$$U_Q = \left[B_Q^2 + P_Q^2\right]^{1/2} = \left[0.101^2 + 0.147^2\right]^{1/2} = \pm 0.178 \text{ in} - \text{lbf}$$

For this sample calculation in which Q = 28.497 in-lbf, this represents an uncertainty of ± 0.62% with 95% confidence. Table A21 presents the uncertainty analysis of model propeller shaft torque for all the individual data spots collected during the self propulsion test. Table 7 is a summary of the propeller shaft torque uncertainty analysis at interpolated whole knot (ship scale) increments.

MODEL PROPELLER SHAFT ROTATION RATE (N)

Propeller shaft rotation rate is determined with instrumentation that is very similar to that used to determine model speed. Rotation rate is determined by counting the number of voltage pulses originating in a magnetic pickup. A stationary magnetic pickup senses the teeth on a small gear concentric on the propeller shaft. Each tooth encounter produces one voltage pulse (square wave). The gear has 60 teeth. In the instant that data collection begins, the pulse counter is initiated. However, the counter's internal clock (time base) does not mark time until the first gear tooth is encountered. Counter time ends as the last gear tooth is encountered. Total counter time, t, is thereby associated with the correct integer number of pulses. Total counter time, t, varies with pulse frequency and is, in general, different by milliseconds than the 5 second data sampling

period. During the time period, t, the total number of voltage pulses, n, is summed by the pulse counter and entered into the computer as frequency, f = n/t. Shaft rotation rate, N, is then calculated:

$$N = \frac{f}{60} \text{Hz}$$

For this sample calculation, N = 469.7 RPM = 7.828 Hz (Table A10, data spot 181).

Rotation Rate Bias Limit (B_N).

One elemental bias error is associated with propeller shaft rotation rate:

1. *B_f: Pulse Frequency Bias Limit:*

Manufacturer's specifications state that the accuracy of the pulse counter in determining frequency is:

Accuracy = ± resolution ± f (time base error) = ± 0.0068 pulses/second

Where resolution = ± LSD ± 1.4 f (trigger error/gate time)
LSD = least significant digit = 0.0001 pulses/second
f = nominal frequency (@ N= 469.7 RPM) = 469.7 pulses/second
trigger error = 0.000015 sec
gate time (nominal) = 5 sec
time base error = 0.00001

This specified accuracy refers to the bias limit inherent in the pulse counter itself and is therefore a zeroth-order bias limit estimate.

$$B_f = 0.0068 \text{ pulses/second}$$

The pulse frequency bias limit is propagated through the uncertainty analysis expression to obtain the bias limit for measured propeller shaft rotation rate:

$$B_N = \frac{\partial N}{\partial f} B_f = \frac{1}{60} 0.0068 = \pm 0.0001 \text{ Hz} = \pm 0.007 \text{ RPM}$$

Rotation Rate Precision Limit (P_N).

The precision limit for model propeller shaft rotation rate, P_N, is determined with the same method as that detailed previously. Tables A11 through A13 show that P_N is calculated to be ± 0.047 RPM at 13 knots, ± 0.081 RPM at 17 knots and ± 0.113 RPM at 20 knots. These three values of P_N are plotted and curve fit in Figure A7. Values for P_N may now be determined from the curve for any value of propeller shaft rotation rate, N. Table A22 presents the values of P_N

determined in this way. For this sample calculation, where measured N = 469.7 RPM (Table A10, data spot 181):

$$P_N = \pm 0.112 \text{ RPM}$$

Rotation Rate Overall Uncertainty (U_N).

The bias and precision error limits are now combined to obtain the overall uncertainty in the value of measured model propeller shaft rotation rate, U_N.

$$U_N = \left[B_N^2 + P_N^2\right]^{1/2} = \left[0.007^2 + 0.112^2\right]^{1/2} = \pm 0.11 \text{ RPM}$$

For this sample calculation in which N = 469.7 RPM, this represents an uncertainty of ± 0.02% with 95% confidence. Table A23 presents the uncertainty analysis of model propeller shaft rotation rate for all the individual data spots collected during the self propulsion test. Table 8 is a summary of the propeller shaft rotation rate uncertainty analysis at interpolated whole knot (ship scale) increments.

OVERALL UNCERTAINTY IN THE RESULT (U_{PD}).

Elemental bias and precision error limits were determined and combined, above, to obtain the bias and precision error limits for the measured quantities, model propeller shaft rotation rate (N) and torque (Q). Now these individual measurement error limits are propagated through the uncertainty analysis expression to obtain the bias and precision limits and the overall uncertainty for the experimental result, model scale delivered power (PD):

$$PD = \frac{Q \times N \times 2\pi}{12 \times 33000} = \frac{Q \times N}{63{,}025}$$

Where Q = Model Torque = 28.497 (in-lbf)
N = Model Propeller Rotation Rate = 469.7 (RPM)
and 12 in / ft
33000 ft -lbf / min -Hp

The first order bias and precision limits for Delivered Power, PD, are calculated

$$B_{PD} = \left[\left(\frac{\partial PD}{\partial Q} B_Q\right)^2 + \left(\frac{\partial PD}{\partial N} B_N\right)^2\right]^{1/2}$$

$$P_{PD} = \left[\left(\frac{\partial PD}{\partial Q} P_Q \right)^2 + \left(\frac{\partial PD}{\partial N} P_N \right)^2 \right]^{1/2}$$

The required partial derivatives are obtained from the original equation for PD:

$$\frac{\partial PD}{\partial Q} = \frac{N}{63025} = \frac{469.7}{63025} = 0.0075 \quad \text{and} \quad \frac{\partial PD}{\partial N} = \frac{Q}{63025} = \frac{28.497}{63025} = 0.0005$$

The previously determined bias and precision limits are :

$B_Q = 0.101$ in-lbf, $B_N = 0.007$ RPM, $P_Q = 0.147$ in-lbf, $P_N = 0.112$ RPM

Substituting :

$$B_{PD} = \left[(0.0075 \times 0.101)^2 + (0.0005 \times 0.007)^2 \right]^{1/2} = \pm 0.0008 \text{ Hp}$$

$$P_{PD} = \left[(0.0075 \times 0.147)^2 + (0.0005 \times 0.112)^2 \right]^{1/2} = \pm 0.0011 \text{ Hp}$$

The overall uncertainty in model scale delivered power is:

$$U_{PD} = \left[(B_{PD})^2 + (P_{PD})^2 \right]^{1/2} = \left[(0.0008)^2 + (0.0011)^2 \right]^{1/2} = \pm 0.0014 \text{ Hp}$$

Or, the true value of model scale delivered power for this sample data spot is 0.212 Hp ± 0.0014 Hp (± 0.66%) at the 95% confidence level.

Table A24 presents the delivered power, PD, uncertainty analysis (U_{PD}) for all the individual data spots collected during the self propulsion test. Table 9 is a summary of the PD uncertainty analysis at interpolated whole knot (ship scale) increments.

CONCLUSIONS

A method for analyzing the uncertainties in the experimental measurements and the results of ship model resistance and self propulsion tests has been developed. The method has been applied to the data from experiments with DTMB Model 5326-2. The set of sample calculations presented in the text provides an outline or standard that may be applied to future experiments. The results of the sample calculations are summarized in Table 10.

For all the experimental measurements, the most significant contributor to the overall uncertainty is, consistently, the precision limit. This is primarily an indication of the level of unsteadiness in the process being measured.

Bias limits are acceptably small, indicating reasonable and satisfactory experimental design and technique.

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Table 1. Summary of uncertainty analysis of measured model speed (U_V), resistance test.

Ship Speed Vs (kts)	Model Speed V (ft/sec)	Elemental Bias Errors B_D (± ft)	Elemental Bias Errors B_f (± pulses/sec)	Bias Limit Bv (± ft/sec)	Precision Limit Pv (± ft/sec)	Overall Uncertainty Uv (± ft/sec)	Overall Uncertainty Uv (± %)
10.00	3.330	0.00042	0.0048	0.001	0.002	0.002	0.06
11.00	3.664	0.00042	0.0053	0.001	0.002	0.002	0.07
12.00	3.997	0.00042	0.0058	0.001	0.003	0.003	0.07
13.00	4.330	0.00042	0.0062	0.001	0.003	0.003	0.07
14.00	4.663	0.00042	0.0067	0.001	0.003	0.003	0.07
15.00	4.996	0.00042	0.0072	0.001	0.003	0.004	0.07
16.00	5.329	0.00042	0.0077	0.001	0.004	0.004	0.07
17.00	5.662	0.00042	0.0081	0.001	0.004	0.004	0.08
18.00	5.995	0.00042	0.0086	0.002	0.004	0.005	0.08
19.00	6.328	0.00042	0.0091	0.002	0.005	0.005	0.08
20.00	6.661	0.00042	0.0096	0.002	0.005	0.005	0.08
21.00	6.994	0.00042	0.0100	0.002	0.005	0.005	0.08
22.00	7.327	0.00042	0.0105	0.002	0.006	0.006	0.08
23.00	7.660	0.00042	0.0110	0.002	0.006	0.006	0.08

Table 2. Summary of uncertainty analysis of measured model total resistance (U_{RT}), resistance test.

Ship Speed Vs (kts)	Model Speed V (ft/sec)	Model Total Resistance R_T (lbf)	Elemental Bias Errors B_{std} (± lbf)	B_{cf} (± lbf)	B_e (± lbf)	B_{data} (± lbf)	$B_{install}$ (± lbf)	$B_{concept}$ (± lbf)	Bias Limit B_{R_T} (± lbf)	Precision Limit P_{R_T} (± lbf)	Overall Uncertainty U_{R_T} (± lbf)	Overall Uncertainty U_{R_T} (± %)
10.0	3.330	4.518	0.0005	0.0550	0.0013	0.0140	0.0002	0.0000	0.057	0.181	0.190	4.20
11.0	3.664	5.395	0.0005	0.0550	0.0013	0.0140	0.0002	0.0000	0.057	0.188	0.197	3.64
12.0	3.997	6.343	0.0006	0.0550	0.0013	0.0140	0.0002	0.0000	0.057	0.196	0.204	3.22
13.0	4.330	7.351	0.0006	0.0550	0.0013	0.0140	0.0003	0.0000	0.057	0.204	0.212	2.89
14.0	4.663	8.419	0.0007	0.0550	0.0013	0.0140	0.0003	0.0000	0.057	0.213	0.221	2.62
15.0	4.996	9.527	0.0007	0.0550	0.0013	0.0140	0.0004	0.0000	0.057	0.223	0.230	2.41
16.0	5.329	10.660	0.0007.	0.0550	0.0013	0.0140	0.0004	0.0000	0.057	0.232	0.239	2.24
17.0	5.662	11.895	0.0008	0.0550	0.0013	0.0140	0.0005	0.0000	0.057	0.242	0.249	2.09
18.0	5.995	13.256	0.0008	0.0550	0.0013	0.0140	0.0005	0.0000	0.057	0.254	0.260	1.96
19.0	6.328	14.753	0.0009	0.0550	0.0013	0.0140	0.0006	0.0000	0.057	0.266	0.272	1.84
20.0	6.661	16.417	0.0009	0.0550	0.0013	0.0140	0.0006	0.0000	0.057	0.280	0.285	1.74
21.0	6.994	18.429	0.0010	0.0550	0.0013	0.0140	0.0007	0.0000	0.057	0.296	0.302	1.64
22.0	7.327	21.219	0.0010	0.0550	0.0013	0.0140	0.0008	0.0000	0.057	0.320	0.325	1.53
23.0	7.660	26.242	0.0011	0.0550	0.0013	0.0140	0.0010	0.0000	0.057	0.361	0.366	1.39

Table 3. Summary of uncertainty analysis of calculated coefficient of total resistance (U_{CT}), resistance test.

Ship Speed Vs (kts)	Model Speed V (ft/sec)	Total Res. R_T (lbf)	C_T (10^{-3})	$\delta C_T/\delta R_T$ (1/lbf)	$\delta C_T/\delta \rho$ 1/(lbfs^2/ft^4)	$\delta C_T/\delta V$ 1/(ft/s)	B_{R_T} (± lbf)	B_ρ (± lbfs^2/ft^4)	B_V (± ft/s)	B_{C_T} ±(10^{-5})	P_{R_T} (± lbf)	P_V (± ft/s)	P_{C_T} ±(10^{-5})	U_{C_T} ±(10^{-5})	U_{C_T} ±%
10.0	3.330	4.518	3.61	0.0008	-0.0019	-0.0022	0.057	0.007	0.0008	4.72	0.181	0.0019	14.45	15.20	4.21
11.0	3.664	5.395	3.56	0.0007	-0.0018	-0.0019	0.057	0.007	0.0009	3.96	0.188	0.0022	12.42	13.03	3.66
12.0	3.997	6.343	3.51	0.0006	-0.0018	-0.0018	0.057	0.007	0.0010	3.40	0.196	0.0025	10.87	11.39	3.24
13.0	4.330	7.351	3.47	0.0005	-0.0018	-0.0016	0.057	0.007	0.0011	2.96	0.204	0.0028	9.66	10.11	2.91
14.0	4.663	8.419	3.43	0.0004	-0.0018	-0.0015	0.057	0.007	0.0012	2.63	0.213	0.0031	8.70	9.08	2.65
15.0	4.996	9.527	3.38	0.0004	-0.0017	-0.0014	0.057	0.007	0.0013	2.36	0.223	0.0034	7.90	8.25	2.44
16.0	5.329	10.660	3.32	0.0003	-0.0017	-0.0012	0.057	0.007	0.0014	2.15	0.232	0.0037	7.24	7.55	2.27
17.0	5.662	11.895	3.28	0.0003	-0.0017	-0.0012	0.057	0.007	0.0014	1.97	0.242	0.0040	6.70	6.99	2.13
18.0	5.995	13.256	3.26	0.0002	-0.0017	-0.0011	0.057	0.007	0.0015	1.84	0.254	0.0043	6.26	6.52	2.00
19.0	6.328	14.753	3.26	0.0002	-0.0017	-0.0010	0.057	0.007	0.0016	1.73	0.266	0.0046	5.90	6.15	1.88
20.0	6.661	16.417	3.27	0.0002	-0.0017	-0.0010	0.057	0.007	0.0017	1.65	0.280	0.0049	5.60	5.84	1.78
21.0	6.994	18.429	3.33	0.0002	-0.0017	-0.0010	0.057	0.007	0.0018	1.59	0.296	0.0052	5.39	5.62	1.68
22.0	7.327	21.219	3.50	0.0002	-0.0018	-0.0010	0.057	0.007	0.0019	1.58	0.320	0.0055	5.30	5.53	1.58
23.0	7.660	26.242	3.96	0.0002	-0.0020	-0.0010	0.057	0.007	0.0019	1.68	0.361	0.0058	5.48	5.73	1.45

Table 4. Summary of uncertainty analysis of measured model speed (U_V), self propulsion test.

Ship Speed Vs (kts)	Model Speed V (ft/sec)	Elemental Bias Errors B_D (± ft)	Elemental Bias Errors B_f (± pulses/sec)	Bias Limit B_V (± ft/sec)	Precision Limit P_V (± ft/sec)	Overall Uncertainty U_V (± ft/sec)	Overall Uncertainty U_V (± %)
10.0	3.330	0.00042	0.0048	0.001	0.001	0.001	0.04
11.0	3.664	0.00042	0.0053	0.001	0.001	0.002	0.04
12.0	3.997	0.00042	0.0058	0.001	0.002	0.002	0.05
13.0	4.330	0.00042	0.0062	0.001	0.002	0.002	0.05
14.0	4.663	0.00042	0.0067	0.001	0.002	0.002	0.05
15.0	4.996	0.00042	0.0072	0.001	0.002	0.002	0.05
16.0	5.329	0.00042	0.0077	0.001	0.002	0.003	0.05
17.0	5.662	0.00042	0.0081	0.001	0.002	0.003	0.05
18.0	5.995	0.00042	0.0086	0.002	0.003	0.003	0.05
19.0	6.328	0.00042	0.0091	0.002	0.003	0.003	0.05
20.0	6.661	0.00042	0.0096	0.002	0.003	0.003	0.05
21.0	6.994	0.00042	0.0100	0.002	0.003	0.004	0.05
22.0	7.327	0.00042	0.0105	0.002	0.003	0.004	0.05
23.0	7.660	0.00042	0.0110	0.002	0.004	0.004	0.05

Table 5. Summary of uncertainty analysis of measured model tow force (U_{FD}), self propulsion test.

Ship Speed Vs (kts)	Model Speed V (ft/sec)	Model Tow Force Fd (lbf)	Elemental Bias Errors						Bias Limit B_{Fd} (± lbf)	Precision Limit P_{Fd} (± lbf)	Overall Uncertainty U_{Fd}	
			B_{std} (± lbf)	B_{cf} (± lbf)	B_e (± lbf)	B_{data} (± lbf)	$B_{install}$ (± lbf)	$B_{concept}$ (± lbf)			(± lbf)	(± %)
10.0	3.330	1.292	0.0001	0.0055	0.0007	0.0140	0.0000	0.0000	0.015	0.065	0.066	5.14
11.0	3.664	1.511	0.0001	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.069	0.071	4.70
12.0	3.997	1.742	0.0001	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.074	0.076	4.35
13.0	4.330	1.986	0.0001	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.080	0.081	4.08
14.0	4.663	2.241	0.0001	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.085	0.086	3.85
15.0	4.996	2.508	0.0002	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.091	0.092	3.67
16.0	5.329	2.786	0.0002	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.097	0.098	3.51
17.0	5.662	3.075	0.0002	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.103	0.104	3.38
18.0	5.995	3.374	0.0002	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.109	0.110	3.27
19.0	6.328	3.684	0.0002	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.116	0.117	3.17
20.0	6.661	4.004	0.0002	0.0055	0.0007	0.0140	0.0002	0.0000	0.015	0.123	0.124	3.09
21.0	6.994	4.333	0.0002	0.0055	0.0007	0.0140	0.0002	0.0000	0.015	0.130	0.131	3.02
22.0	7.327	4.672	0.0002	0.0055	0.0007	0.0140	0.0002	0.0000	0.015	0.137	0.138	2.95
23.0	7.660	5.021	0.0002	0.0055	0.0007	0.0140	0.0002	0.0000	0.015	0.145	0.145	2.90

Table 6. Summary of uncertainty analysis of measured model propeller shaft thrust (U_T), self propulsion test.

Ship Speed Vs (kts)	Model Speed V (ft/sec)	Model Prop. Shaft Thrust T (lbf)	Elemental Bias Errors						Bias Limit B_T (± lbf)	Precision Limit P_T (± lbf)	Overall Uncertainty U_T	
			B_{std} (± lbf)	B_{cf} (± lbf)	B_e (± lbf)	B_{data} (± lbf)	$B_{install}$ (± lbf)	$B_{concept}$ (± lbf)			(± lbf)	(± %)
10.0	3.330	3.680	0.0077	0.0344	0.0012	0.0114	0.0410	0.0000	0.055	0.023	0.060	1.62
11.0	3.664	4.460	0.0094	0.0344	0.0012	0.0114	0.0410	0.0000	0.056	0.028	0.062	1.40
12.0	3.997	5.320	0.0112	0.0344	0.0012	0.0114	0.0410	0.0000	0.056	0.035	0.066	1.24
13.0	4.330	6.220	0.0131	0.0344	0.0012	0.0114	0.0410	0.0000	0.056	0.041	0.070	1.12
14.0	4.663	7.150	0.0150	0.0344	0.0012	0.0114	0.0410	0.0000	0.057	0.048	0.074	1.04
15.0	4.996	8.070	0.0170	0.0344	0.0012	0.0114	0.0410	0.0000	0.057	0.055	0.079	0.98
16.0	5.329	9.030	0.0190	0.0344	0.0012	0.0114	0.0410	0.0000	0.058	0.062	0.085	0.94
17.0	5.662	10.160	0.0213	0.0344	0.0012	0.0114	0.0410	0.0000	0.059	0.070	0.091	0.90
18.0	5.995	11.450	0.0241	0.0344	0.0012	0.0114	0.0410	0.0000	0.060	0.079	0.099	0.87
19.0	6.328	13.020	0.0273	0.0344	0.0012	0.0114	0.0410	0.0000	0.061	0.091	0.109	0.84
20.0	6.661	14.730	0.0309	0.0344	0.0012	0.0114	0.0410	0.0000	0.063	0.103	0.121	0.82
21.0	6.994	16.700	0.0351	0.0344	0.0012	0.0114	0.0410	0.0000	0.065	0.118	0.134	0.80
22.0	7.327	19.400	0.0407	0.0344	0.0012	0.0114	0.0410	0.0000	0.068	0.137	0.153	0.79
23.0	7.660	24.880	0.0523	0.0344	0.0012	0.0114	0.0410	0.0000	0.076	0.177	0.193	0.77

Table 7. Summary of uncertainty analysis of measured model propeller shaft torque (U_Q), self propulsion test.

Ship Speed Vs (kts)	Model Speed V (ft/sec)	Model Prop. Shaft Torque Q (in-lbf)	Elemental Bias Errors						Bias Limit	Precision Limit	Overall Uncertainty	
			B_{std} (± in-lbf)	B_{cf} (±in-lbf)	B_e (±in-lbf)	B_{data} (±in-lbf)	$B_{install}$ (±in-lbf)	$B_{concept}$ (± in-lbf)	B_Q (± in-lbf)	P_Q (± in-lbf)	U_Q (± in-lbf)	(± %)
10.0	3.330	7.360	0.0037	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.055	0.114	1.55
11.0	3.664	8.920	0.0045	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.062	0.118	1.32
12.0	3.997	10.630	0.0054	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.070	0.122	1.15
13.0	4.330	12.390	0.0063	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.077	0.126	1.02
14.0	4.663	14.040	0.0071	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.084	0.131	0.93
15.0	4.996	15.810	0.0080	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.092	0.136	0.86
16.0	5.329	17.780	0.0090	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.101	0.142	0.80
17.0	5.662	19.990	0.0101	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.110	0.149	0.75
18.0	5.995	22.560	0.0114	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.121	0.157	0.70
19.0	6.328	25.330	0.0127	0.0834	0.0019	0.0199	0.0510	0.0000	0.101	0.133	0.167	0.66
20.0	6.661	28.550	0.0144	0.0834	0.0019	0.0199	0.0510	0.0000	0.101	0.147	0.178	0.62
21.0	6.994	32.560	0.0164	0.0834	0.0019	0.0199	0.0510	0.0000	0.101	0.165	0.193	0.59
22.0	7.327	37.650	0.0189	0.0834	0.0019	0.0199	0.0510	0.0000	0.102	0.187	0.212	0.56
23.0	7.660	46.960	0.0236	0.0834	0.0019	0.0199	0.0510	0.0000	0.103	0.227	0.249	0.53

Table 8. Summary of uncertainty analysis of measured model propeller shaft rotation rate (U_N), self propulsion test.

Ship Speed Vs (kts)	Model Speed V (ft/sec)	Model Prop. Shaft Rotation Rate N (RPM)	Elemental Bias Error B_f (± pulses/sec)	Bias Limit B_N (± RPM)	Precision Limit P_N (± RPM)	Overall Uncertainty U_N (± RPM)	(± %)
10.0	3.330	230.56	0.0034	0.003	0.017	0.017	0.01
11.0	3.664	255.78	0.0037	0.004	0.027	0.027	0.01
12.0	3.997	280.10	0.0041	0.004	0.037	0.037	0.01
13.0	4.330	301.71	0.0044	0.004	0.045	0.046	0.02
14.0	4.663	323.39	0.0047	0.005	0.054	0.054	0.02
15.0	4.996	345.83	0.0050	0.005	0.063	0.063	0.02
16.0	5.329	367.85	0.0053	0.005	0.072	0.072	0.02
17.0	5.662	390.47	0.0056	0.006	0.081	0.081	0.02
18.0	5.995	413.83	0.0060	0.006	0.090	0.090	0.02
19.0	6.328	438.88	0.0063	0.006	0.100	0.100	0.02
20.0	6.661	465.50	0.0067	0.007	0.111	0.111	0.02
21.0	6.994	493.48	0.0071	0.007	0.122	0.122	0.02
22.0	7.327	528.67	0.0076	0.008	0.136	0.136	0.03
23.0	7.660	582.48	0.0084	0.008	0.157	0.158	0.03

Table 9. Summary of uncertainty analysis of calculated model scale delivered power (U_{PD}), self propulsion test.

Ship Speed Vs (kts)	Model Speed V (ft/sec)	Q (in-lbf)	N (RPM)	PD (Hp)	δPD/δQ (Hp/in-lbf)	δPD/δN (Hp-min)	B_Q (in-lbf)	B_N (RPM)	B_{PD} (Hp)	P_Q (in-lbf)	P_N (RPM)	P_{PD} (Hp)	U_{PD} (Hp)	U_{PD} (%)
10.0	3.330	7.360	230.56	0.027	0.0037	0.0001	0.100	0.003	0.0004	0.055	0.017	0.0002	0.0004	1.55
11.0	3.664	8.920	255.78	0.036	0.0041	0.0001	0.100	0.004	0.0004	0.062	0.027	0.0003	0.0005	1.32
12.0	3.997	10.630	280.10	0.047	0.0044	0.0002	0.100	0.004	0.0004	0.070	0.037	0.0003	0.0005	1.15
13.0	4.330	12.390	301.71	0.059	0.0048	0.0002	0.100	0.004	0.0005	0.077	0.045	0.0004	0.0006	1.02
14.0	4.663	14.040	323.39	0.072	0.0051	0.0002	0.100	0.005	0.0005	0.084	0.054	0.0004	0.0007	0.93
15.0	4.996	15.810	345.83	0.087	0.0055	0.0003	0.100	0.005	0.0005	0.092	0.063	0.0005	0.0007	0.86
16.0	5.329	17.780	367.85	0.104	0.0058	0.0003	0.100	0.005	0.0006	0.101	0.072	0.0006	0.0008	0.80
17.0	5.662	19.990	390.47	0.124	0.0062	0.0003	0.100	0.006	0.0006	0.110	0.081	0.0007	0.0009	0.75
18.0	5.995	22.560	413.83	0.148	0.0066	0.0004	0.100	0.006	0.0007	0.121	0.090	0.0008	0.0010	0.70
19.0	6.328	25.330	438.88	0.176	0.0070	0.0004	0.101	0.006	0.0007	0.133	0.100	0.0009	0.0012	0.66
20.0	6.661	28.550	465.50	0.211	0.0074	0.0005	0.101	0.007	0.0007	0.147	0.111	0.0011	0.0013	0.63
21.0	6.994	32.560	493.48	0.255	0.0078	0.0005	0.101	0.007	0.0008	0.165	0.122	0.0013	0.0015	0.59
22.0	7.327	37.650	528.67	0.316	0.0084	0.0006	0.102	0.008	0.0009	0.187	0.136	0.0016	0.0018	0.56
23.0	7.660	46.960	582.48	0.434	0.0092	0.0007	0.103	0.008	0.0009	0.227	0.157	0.0021	0.0023	0.53

Table 10. Summary of uncertainty analysis sample calculations, resistance and self propulsion tests.

	Units	Nominal Mean (units)	Bias Limit (± units)	Precision Limit (± units)	Uncertainty* (± units)	Uncertainty* (± %)
Resistance Test:						
Speed (V)	ft/sec	6.681	0.002	0.005	0.005	0.08
Total Resistance (R_T)	lbf	16.469	0.057	0.280	0.286	1.74
Coefficient of Total Resistance (C_T)		3.27 E-3	1.66 E-5	5.62 E-5	5.86 E-5	1.79
Self Propulsion Test:						
Speed (V)	ft/sec	6.692	0.002	0.003	0.003	0.05
Tow force (Fd)	lbf	4.123	0.015	0.125	0.126	3.06
Propeller shaft thrust (T)	lbf	14.738	0.063	0.103	0.121	0.82
Propeller shaft torque (Q)	in-lbf	28.497	0.101	0.147	0.178	0.62
Propeller shaft revolution rate (N)	RPM	469.7	0.007	0.112	0.112	0.02
Delivered Power (PD)	Hp	0.212	0.0008	0.0011	0.0014	0.66

* Uncertainty is calculated by the root-sum-square (RSS) method for a 95% confidence level

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APPENDIX A

MODEL TEST DATA AND CALCULATIONS

APPENDIX A - MODEL TEST DATA AND CALCULATIONS

FIGURES

TABLES

TABLES (continued)

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Table A1. Resistance test data.

Spot Number	Model Speed: V (ft/s)	Model Total Resistance: R_T (lbf)	Corresponding Ship Speed (knots)
1	3.359	4.354	10.086
2	3.359	4.318	10.086
3	3.359	4.461	10.086
4	5.016	9.468	15.061
5	5.018	9.698	15.067
6	5.017	9.533	15.064
7	6.019	13.497	18.072
8	6.021	13.215	18.078
9	6.018	13.244	18.069
10	4.366	7.464	13.110
11	4.365	7.466	13.108
12	4.365	7.624	13.107
13	4.368	7.491	13.115
14	4.367	7.437	13.112
15	4.368	7.600	13.115
16	4.367	7.393	13.111
17	4.367	7.410	13.112
18	4.369	7.600	13.117
19	4.366	7.521	13.109
20	4.366	7.549	13.109
21	4.366	7.580	13.108
22	4.368	7.365	13.114
23	4.368	7.437	13.115
24	4.367	7.324	13.111
25	4.368	7.380	13.115
26	4.366	7.543	13.110
27	4.366	7.642	13.110
28	4.364	7.614	13.104
29	4.367	7.568	13.111
30	4.366	7.421	13.110
31	7.673	26.309	23.039
32	7.673	26.070	23.039
33	7.673	26.242	23.039
34	7.672	26.722	23.036
35	3.687	5.317	11.070
36	3.689	5.169	11.076
37	3.688	5.377	11.073
38	4.686	8.513	14.070
39	4.688	8.418	14.076
40	4.689	8.551	14.079
41	6.340	14.730	19.036
42	6.342	14.764	19.042

Table A1. Resistance test data, continued.

Spot Number	Model Speed: V (ft/s)	Model Total Resistance: R_T (lbf)	Corresponding Ship Speed (knots)
43	6.340	14.708	19.036
44	5.688	12.047	17.080
45	5.686	12.015	17.072
46	5.685	11.879	17.071
47	5.689	11.990	17.083
48	5.691	12.020	17.086
49	5.690	12.074	17.085
50	5.691	11.893	17.087
51	5.688	11.941	17.080
52	5.692	12.040	17.090
53	5.690	12.090	17.084
54	5.687	11.854	17.075
55	5.690	11.640	17.086
56	5.688	11.951	17.079
57	5.690	11.717	17.085
58	5.690	11.927	17.084
59	5.690	11.866	17.084
60	5.693	11.965	17.092
61	5.692	12.061	17.091
62	5.693	12.018	17.392
63	5.692	12.105	17.091
64	7.342	21.021	22.045
65	7.343	21.198	22.048
66	7.344	21.395	22.051
67	7.342	21.398	22.045
68	7.342	21.765	22.045
69	4.019	6.468	12.067
70	4.019	6.515	12.067
71	4.018	6.535	12.064
72	5.341	10.779	16.037
73	5.342	10.737	16.040
74	5.339	10.803	16.031
75	7.009	18.452	21.045
76	7.009	18.373	21.045
77	7.009	18.450	21.045
78	7.009	18.538	21.045
79	3.360	4.574	10.089
80	3.359	4.531	10.086
81	4.020	6.401	12.070
82	4.018	6.415	12.064
83	4.695	8.459	14.097
84	4.697	8.646	14.103

Table A1. Resistance test data, continued.

Spot Number	Model Speed: V (ft/s)	Model Total Resistance: R_T (lbf)	Corresponding Ship Speed (knots)
85	6.681	16.469	20.059
86	6.681	16.482	20.059
87	6.682	16.687	20.063
88	6.680	16.695	20.056
89	6.682	16.838	20.063
90	6.684	16.686	20.068
91	6.684	16.570	20.070
92	6.684	16.431	20.069
93	6.683	16.337	20.068
94	6.686	16.537	20.076
95	6.686	16.541	20.076
96	6.684	16.584	20.070
97	6.684	16.510	20.070
98	6.685	16.656	20.072
99	6.687	16.673	20.078
100	6.687	16.531	20.079
101	6.687	16.296	20.077
102	6.687	16.608	20.079
103	6.686	16.852	20.074
104	6.687	16.598	20.077
105	6.687	16.615	20.077
106	6.686	16.572	20.076
107	6.686	16.553	20.074
108	6.017	13.369	18.066
109	6.017	13.400	18.066
110	7.671	26.428	23.033
111	7.668	26.489	23.024
112	3.689	5.362	11.076
113	3.689	5.358	11.076
114	5.012	9.677	15.049
115	5.013	9.571	15.052
116	7.342	21.386	22.045
117	7.340	21.269	22.039
118	5.343	10.536	16.043
119	5.342	10.829	16.040
120	6.345	14.755	19.051
121	6.343	14.777	19.045
122	6.344	14.831	19.048
123	7.011	18.206	21.051
124	7.010	18.229	21.048
125	7.505	23.482	22.534
126	7.502	23.308	22.525
127	7.504	23.697	22.531

Table A2. Calculation of precision limit for measured model speed (P_V) and total resistance (P_{RT}), resistance test, 13 knot ship speed.

Spot Index i = 1,N	Test Spot Number	Ship Speed (knots)	Model Speed (knots)	Model Speed: V (ft/sec)	Model Total Resistance: R_T (lbf)
1	10	13.110	2.587	4.366	7.464
2	11	13.108	2.586	4.365	7.466
3	12	13.107	2.586	4.365	7.624
4	13	13.115	2.588	4.368	7.491
5	14	13.112	2.587	4.367	7.437
6	15	13.115	2.588	4.368	7.600
7	16	13.111	2.587	4.367	7.393
8	17	13.112	2.587	4.367	7.410
9	18	13.117	2.588	4.369	7.600
10	19	13.109	2.587	4.366	7.521
11	20	13.109	2.587	4.366	7.549
12	21	13.108	2.587	4.366	7.580
13	22	13.114	2.588	4.368	7.365
14	23	13.115	2.588	4.368	7.437
15	24	13.111	2.587	4.367	7.324
16	25	13.115	2.588	4.368	7.380
17	26	13.110	2.587	4.366	7.543
18	27	13.110	2.587	4.366	7.642
19	28	13.104	2.586	4.364	7.614
20	29	13.111	2.587	4.367	7.568
21	30	13.110	2.587	4.366	7.421
N = 21	Mean =			4.367	7.497
N-1 = 20	Standard Deviation = Stdev =			0.0012	0.0959
t95(20)=2.086	Precision Limit = Px = t * Stdev =			0.0026	0.2000
	Px / Mean = +/- U (%)			0.059	2.668

Table A3. Calculation of precision limit for measured model speed (P_V) and total resistance (P_{RT}), resistance test, 17 knot ship speed.

Spot Index i = 1,N	Test Spot Number	Ship Speed (knots)	Model Speed (knots)	Model Speed: V (ft/sec)	Model Total Resistance: R_T (lbf)
1	44	17.080	3.370	5.688	12.047
2	45	17.072	3.369	5.686	12.015
3	46	17.071	3.369	5.685	11.879
4	47	17.083	3.371	5.689	11.990
5	48	17.086	3.372	5.691	12.020
6	49	17.085	3.371	5.690	12.074
7	50	17.087	3.372	5.691	11.893
8	51	17.080	3.370	5.688	11.941
9	52	17.090	3.372	5.692	12.040
10	53	17.084	3.371	5.690	12.090
11	54	17.075	3.369	5.687	11.854
12	55	17.086	3.372	5.690	11.640
13	56	17.079	3.370	5.688	11.951
14	57	17.085	3.371	5.690	11.717
15	58	17.084	3.371	5.690	11.927
16	59	17.084	3.371	5.690	11.866
17	60	17.092	3.373	5.693	11.965
18	61	17.091	3.373	5.692	12.061
19	62	17.092	3.373	5.693	12.018
20	63	17.091	3.373	5.692	12.105

N = 20	Mean =	5.690	11.955
N-1 = 19	Standard Deviation = Stdev =	0.0022	0.1213
t95(19)=2.093	Precision Limit = Px = t * Stdev =	0.0046	0.2539
	Px / Mean = +/- U (%)	0.082	2.124

Table A4. Calculation of precision limit for measured model speed (P_V) and total resistance (P_{RT}), resistance test, 20 knot ship speed.

Spot Index i = 1,N	Test Spot Number	Ship Speed (knots)	Model Speed (knots)	Model Speed: V (ft/sec)	Model Total Resistance: R_T (lbf)
1	85	20.059	3.958	6.681	16.469
2	86	20.059	3.958	6.681	16.482
3	87	20.063	3.959	6.682	16.687
4	88	20.056	3.958	6.680	16.695
5	89	20.063	3.959	6.682	16.838
6	90	20.068	3.960	6.684	16.686
7	91	20.070	3.960	6.684	16.570
8	92	20.069	3.960	6.684	16.431
9	93	20.068	3.960	6.683	16.337
10	94	20.076	3.961	6.686	16.537
11	95	20.076	3.962	6.686	16.541
12	96	20.070	3.960	6.684	16.584
13	97	20.070	3.960	6.684	16.510
14	98	20.072	3.961	6.685	16.656
15	99	20.078	3.962	6.687	16.673
16	100	20.079	3.962	6.687	16.531
17	101	20.077	3.962	6.687	16.296
18	102	20.079	3.962	6.687	16.608
19	103	20.074	3.961	6.686	16.852
20	104	20.077	3.962	6.687	16.598
21	105	20.077	3.962	6.687	16.615
22	106	20.076	3.962	6.686	16.572
23	107	20.074	3.961	6.686	16.553

N = 23	Mean =	6.685	16.579
N-1 = 22	Standard Deviation = Stdev =	0.0022	0.1329
t95(22)=2.074	Precision Limit = Px = t * Stdev =	0.0046	0.2756
	Px / Mean = +/- U (%)	0.069	1.663

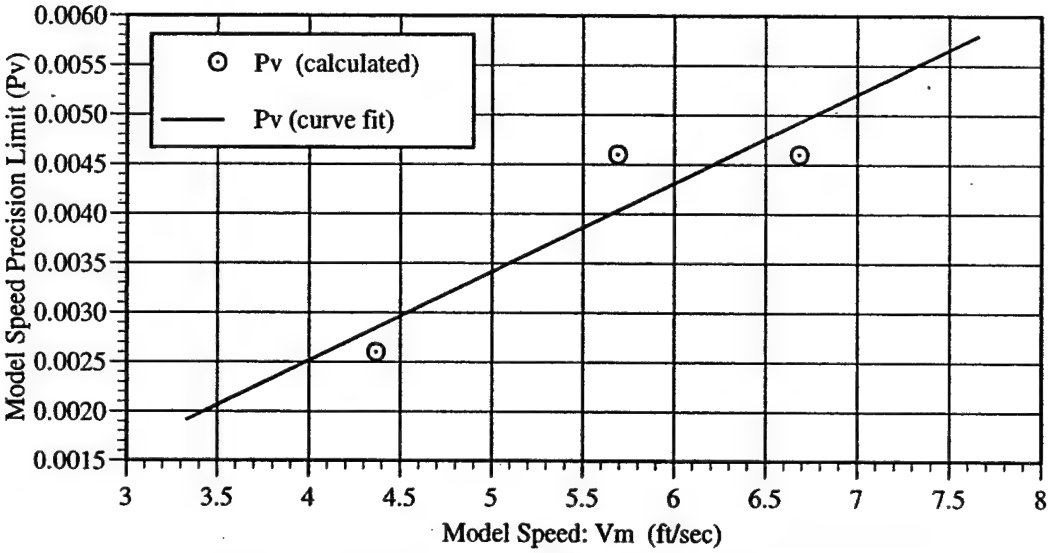

Fig. A1. Model speed precision limit (Pv), resistance test.

Table A5. Interpolated values of model speed precision limit (P_V), resistance test.

Ship Speed Vs (knots)	Model Speed V (ft/s)	Pv (curve fit) (± ft/s)	Pv (± %)	V + Pv (ft/s)	V - Pv (ft/s)
10.00	3.330	0.0019	0.057	3.332	3.328
11.00	3.664	0.0022	0.060	3.666	3.662
12.00	3.997	0.0025	0.063	4.000	3.994
13.00	4.330	0.0028	0.065	4.333	4.327
14.00	4.663	0.0031	0.067	4.666	4.660
15.00	4.996	0.0034	0.068	4.999	4.993
16.00	5.329	0.0037	0.070	5.333	5.325
17.00	5.662	0.0040	0.071	5.666	5.658
18.00	5.995	0.0043	0.072	5.999	5.991
19.00	6.328	0.0046	0.073	6.333	6.323
20.00	6.661	0.0049	0.074	6.666	6.656
21.00	6.994	0.0052	0.074	6.999	6.989
22.00	7.327	0.0055	0.075	7.333	7.321
23.00	7.660	0.0058	0.076	7.666	7.654

Table A6. Uncertainty analysis of measured model speed (U_V), resistance test.

Data Spot No.	Model Speed V (ft/s)	Elemental Bias Errors B_D (ft)	Elemental Bias Errors B_f (1/sec)	Bias Limit B_V (± ft/s)	Precision Limit P_V (± ft/s)	Overall Uncertainty U_V (± ft/s)	Overall Uncertainty U_V (± %)
1	3.359	0.00042	0.0049	0.0009	0.0019	0.0021	0.06
2	3.359	0.00042	0.0049	0.0009	0.0019	0.0021	0.06
3	3.359	0.00042	0.0049	0.0009	0.0019	0.0021	0.06
4	5.016	0.00042	0.0072	0.0013	0.0034	0.0037	0.07
5	5.018	0.00042	0.0072	0.0013	0.0034	0.0037	0.07
6	5.017	0.00042	0.0072	0.0013	0.0034	0.0037	0.07
7	6.019	0.00042	0.0086	0.0015	0.0043	0.0046	0.08
8	6.021	0.00042	0.0086	0.0015	0.0043	0.0046	0.08
9	6.018	0.00042	0.0086	0.0015	0.0043	0.0046	0.08
10	4.366	0.00042	0.0063	0.0011	0.0028	0.0031	0.07
11	4.365	0.00042	0.0063	0.0011	0.0028	0.0031	0.07
12	4.365	0.00042	0.0063	0.0011	0.0028	0.0031	0.07
13	4.368	0.00042	0.0063	0.0011	0.0028	0.0031	0.07
14	4.367	0.00042	0.0063	0.0011	0.0028	0.0031	0.07
15	4.368	0.00042	0.0063	0.0011	0.0028	0.0031	0.07
16	4.367	0.00042	0.0063	0.0011	0.0028	0.0031	0.07
17	4.367	0.00042	0.0063	0.0011	0.0028	0.0031	0.07
18	4.369	0.00042	0.0063	0.0011	0.0028	0.0031	0.07
19	4.366	0.00042	0.0063	0.0011	0.0028	0.0031	0.07
20	4.366	0.00042	0.0063	0.0011	0.0028	0.0031	0.07
21	4.366	0.00042	0.0063	0.0011	0.0028	0.0031	0.07
22	4.368	0.00042	0.0063	0.0011	0.0028	0.0031	0.07
23	4.368	0.00042	0.0063	0.0011	0.0028	0.0031	0.07
24	4.367	0.00042	0.0063	0.0011	0.0028	0.0031	0.07
25	4.368	0.00042	0.0063	0.0011	0.0028	0.0031	0.07
26	4.366	0.00042	0.0063	0.0011	0.0028	0.0031	0.07
27	4.366	0.00042	0.0063	0.0011	0.0028	0.0031	0.07
28	4.364	0.00042	0.0063	0.0011	0.0028	0.0031	0.07
29	4.367	0.00042	0.0063	0.0011	0.0028	0.0031	0.07
30	4.366	0.00042	0.0063	0.0011	0.0028	0.0031	0.07
31	7.673	0.00042	0.0110	0.0020	0.0058	0.0061	0.08
32	7.673	0.00042	0.0110	0.0020	0.0058	0.0061	0.08
33	7.673	0.00042	0.0110	0.0020	0.0058	0.0061	0.08
34	7.672	0.00042	0.0110	0.0019	0.0058	0.0061	0.08
35	3.687	0.00042	0.0053	0.0009	0.0022	0.0024	0.07
36	3.689	0.00042	0.0053	0.0009	0.0022	0.0024	0.07
37	3.688	0.00042	0.0053	0.0009	0.0022	0.0024	0.07
38	4.686	0.00042	0.0068	0.0012	0.0031	0.0033	0.07
39	4.688	0.00042	0.0068	0.0012	0.0031	0.0034	0.07
40	4.689	0.00042	0.0068	0.0012	0.0031	0.0034	0.07
41	6.340	0.00042	0.0091	0.0016	0.0046	0.0049	0.08
42	6.342	0.00042	0.0091	0.0016	0.0046	0.0049	0.08

Table A6. Uncertainty analysis of measured model speed (U_V), resistance test, continued.

Data Spot No.	Model Speed V (ft/s)	Elemental Bias Errors B_D (ft)	Elemental Bias Errors B_t (1/sec)	Bias Limit B_V (± ft/s)	Precision Limit P_V (± ft/s)	Overall Uncertainty U_V (± ft/s)	Overall Uncertainty U_V (± %)
43	6.340	0.00042	0.0091	0.0016	0.0046	0.0049	0.08
44	5.688	0.00042	0.0082	0.0014	0.0040	0.0043	0.08
45	5.686	0.00042	0.0082	0.0014	0.0040	0.0043	0.08
46	5.685	0.00042	0.0082	0.0014	0.0040	0.0043	0.08
47	5.689	0.00042	0.0082	0.0014	0.0040	0.0043	0.08
48	5.691	0.00042	0.0082	0.0014	0.0040	0.0043	0.08
49	5.690	0.00042	0.0082	0.0014	0.0040	0.0043	0.08
50	5.691	0.00042	0.0082	0.0014	0.0040	0.0043	0.08
51	5.688	0.00042	0.0082	0.0014	0.0040	0.0043	0.08
52	5.692	0.00042	0.0082	0.0014	0.0040	0.0043	0.08
53	5.690	0.00042	0.0082	0.0014	0.0040	0.0043	0.08
54	5.687	0.00042	0.0082	0.0014	0.0040	0.0043	0.08
55	5.690	0.00042	0.0082	0.0014	0.0040	0.0043	0.08
56	5.688	0.00042	0.0082	0.0014	0.0040	0.0043	0.08
57	5.690	0.00042	0.0082	0.0014	0.0040	0.0043	0.08
58	5.690	0.00042	0.0082	0.0014	0.0040	0.0043	0.08
59	5.690	0.00042	0.0082	0.0014	0.0040	0.0043	0.08
60	5.693	0.00042	0.0082	0.0014	0.0040	0.0043	0.08
61	5.692	0.00042	0.0082	0.0014	0.0040	0.0043	0.08
62	5.693	0.00042	0.0082	0.0014	0.0040	0.0043	0.08
63	5.692	0.00042	0.0082	0.0014	0.0040	0.0043	0.08
64	7.342	0.00042	0.0105	0.0019	0.0055	0.0058	0.08
65	7.343	0.00042	0.0105	0.0019	0.0055	0.0058	0.08
66	7.344	0.00042	0.0105	0.0019	0.0055	0.0058	0.08
67	7.342	0.00042	0.0105	0.0019	0.0055	0.0058	0.08
68	7.342	0.00042	0.0105	0.0019	0.0055	0.0058	0.08
69	4.019	0.00042	0.0058	0.0010	0.0025	0.0027	0.07
70	4.019	0.00042	0.0058	0.0010	0.0025	0.0027	0.07
71	4.018	0.00042	0.0058	0.0010	0.0025	0.0027	0.07
72	5.341	0.00042	0.0077	0.0014	0.0037	0.0040	0.07
73	5.342	0.00042	0.0077	0.0014	0.0037	0.0040	0.07
74	5.339	0.00042	0.0077	0.0014	0.0037	0.0040	0.07
75	7.009	0.00042	0.0101	0.0018	0.0052	0.0055	0.08
76	7.009	0.00042	0.0101	0.0018	0.0052	0.0055	0.08
77	7.009	0.00042	0.0101	0.0018	0.0052	0.0055	0.08
78	7.009	0.00042	0.0101	0.0018	0.0052	0.0055	0.08
79	3.360	0.00042	0.0049	0.0009	0.0019	0.0021	0.06
80	3.359	0.00042	0.0049	0.0009	0.0019	0.0021	0.06
81	4.020	0.00042	0.0058	0.0010	0.0025	0.0027	0.07
82	4.018	0.00042	0.0058	0.0010	0.0025	0.0027	0.07
83	4.695	0.00042	0.0068	0.0012	0.0031	0.0034	0.07
84	4.697	0.00042	0.0068	0.0012	0.0031	0.0034	0.07

Table A6. Uncertainty analysis of measured model speed (U_V), resistance test, continued.

Data Spot No.	Model Speed V (ft/s)	Elemental Bias Errors B_D (ft)	Elemental Bias Errors B_t (1/sec)	Bias Limit B_V (± ft/s)	Precision Limit P_V (± ft/s)	Overall Uncertainty U_V (± ft/s)	Overall Uncertainty U_V (± %)
85	**6.681**	**0.00042**	**0.0096**	**0.0017**	**0.0049**	**0.0052**	**0.08**
86	6.681	0.00042	0.0096	0.0017	0.0049	0.0052	0.08
87	6.682	0.00042	0.0096	0.0017	0.0049	0.0052	0.08
88	6.680	0.00042	0.0096	0.0017	0.0049	0.0052	0.08
89	6.682	0.00042	0.0096	0.0017	0.0049	0.0052	0.08
90	6.684	0.00042	0.0096	0.0017	0.0049	0.0052	0.08
91	6.684	0.00042	0.0096	0.0017	0.0049	0.0052	0.08
92	6.684	0.00042	0.0096	0.0017	0.0049	0.0052	0.08
93	6.683	0.00042	0.0096	0.0017	0.0049	0.0052	0.08
94	6.686	0.00042	0.0096	0.0017	0.0049	0.0052	0.08
95	6.686	0.00042	0.0096	0.0017	0.0049	0.0052	0.08
96	6.684	0.00042	0.0096	0.0017	0.0049	0.0052	0.08
97	6.684	0.00042	0.0096	0.0017	0.0049	0.0052	0.08
98	6.685	0.00042	0.0096	0.0017	0.0049	0.0052	0.08
99	6.687	0.00042	0.0096	0.0017	0.0049	0.0052	0.08
100	6.687	0.00042	0.0096	0.0017	0.0049	0.0052	0.08
101	6.687	0.00042	0.0096	0.0017	0.0049	0.0052	0.08
102	6.687	0.00042	0.0096	0.0017	0.0049	0.0052	0.08
103	6.686	0.00042	0.0096	0.0017	0.0049	0.0052	0.08
104	6.687	0.00042	0.0096	0.0017	0.0049	0.0052	0.08
105	6.687	0.00042	0.0096	0.0017	0.0049	0.0052	0.08
106	6.686	0.00042	0.0096	0.0017	0.0049	0.0052	0.08
107	6.686	0.00042	0.0096	0.0017	0.0049	0.0052	0.08
108	6.017	0.00042	0.0086	0.0015	0.0043	0.0046	0.08
109	6.017	0.00042	0.0086	0.0015	0.0043	0.0046	0.08
110	7.671	0.00042	0.0110	0.0019	0.0058	0.0061	0.08
111	7.668	0.00042	0.0110	0.0019	0.0058	0.0061	0.08
112	3.689	0.00042	0.0053	0.0009	0.0022	0.0024	0.07
113	3.689	0.00042	0.0053	0.0009	0.0022	0.0024	0.07
114	5.012	0.00042	0.0072	0.0013	0.0034	0.0037	0.07
115	5.013	0.00042	0.0072	0.0013	0.0034	0.0037	0.07
116	7.342	0.00042	0.0105	0.0019	0.0055	0.0058	0.08
117	7.340	0.00042	0.0105	0.0019	0.0055	0.0058	0.08
118	5.343	0.00042	0.0077	0.0014	0.0037	0.0040	0.07
119	5.342	0.00042	0.0077	0.0014	0.0037	0.0040	0.07
120	6.345	0.00042	0.0091	0.0016	0.0046	0.0049	0.08
121	6.343	0.00042	0.0091	0.0016	0.0046	0.0049	0.08
122	6.344	0.00042	0.0091	0.0016	0.0046	0.0049	0.08
123	7.011	0.00042	0.0101	0.0018	0.0052	0.0055	0.08
124	7.010	0.00042	0.0101	0.0018	0.0052	0.0055	0.08
125	7.505	0.00042	0.0108	0.0019	0.0057	0.0060	0.08
126	7.502	0.00042	0.0108	0.0019	0.0057	0.0060	0.08
127	7.504	0.00042	0.0108	0.0019	0.0057	0.0060	0.08

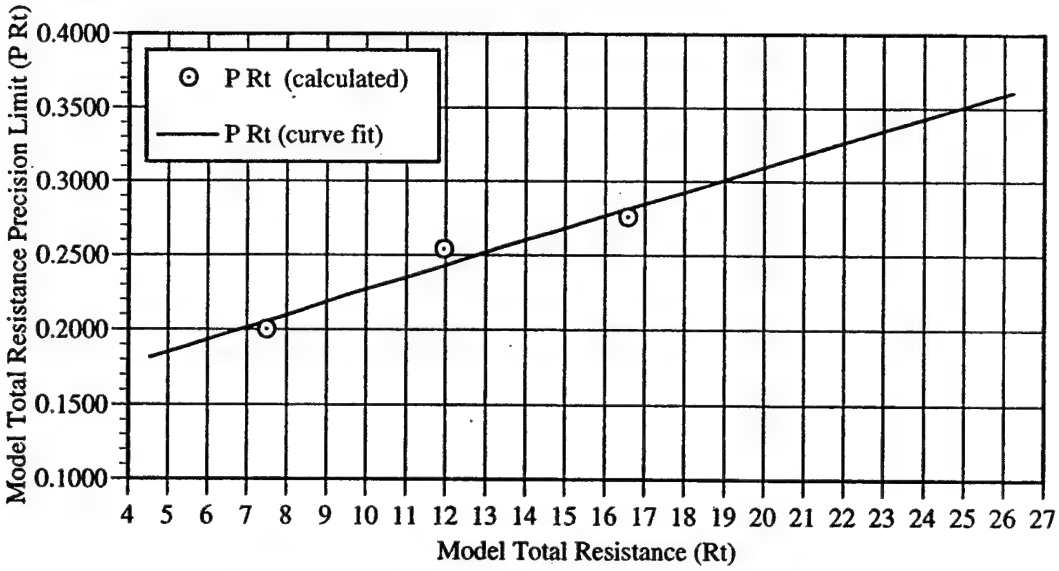

Fig. A2. Model total resistance precision limit (P_{RT}), resistance test.

Table A7. Interpolated values of model total resistance precision limit (P_{RT}), resistance test.

Ship Speed Vs (knots)	Model Speed V (ft/s)	Model Total Resistance: R_T (lbf)	P R_T (curve fit) (± lbf)	P R_T (± %)	R_T + P R_T (lbf)	R_T - P R_T (lbf)
10.00	3.330	4.518	0.181	4.00	4.699	4.337
11.00	3.664	5.395	0.188	3.49	5.583	5.207
12.00	3.997	6.343	0.196	3.09	6.539	6.147
13.00	4.330	7.351	0.204	2.78	7.555	7.147
14.00	4.663	8.419	0.213	2.53	8.632	8.206
15.00	4.996	9.527	0.223	2.34	9.750	9.304
16.00	5.329	10.660	0.232	2.18	10.892	10.428
17.00	5.662	11.895	0.242	2.04	12.137	11.653
18.00	5.995	13.256	0.254	1.91	13.510	13.002
19.00	6.328	14.753	0.266	1.80	15.019	14.487
20.00	6.661	16.417	0.280	1.70	16.697	16.137
21.00	6.994	18.429	0.296	1.61	18.725	18.133
22.00	7.327	21.219	0.320	1.51	21.539	20.899
23.00	7.660	26.242	0.361	1.38	26.603	25.881

Table A8. Uncertainty analysis of measured model total resistance (U_{RT}), resistance test.

Data Spot No.	Model Total Resistance R_T (lbf)	Elemental Bias Errors						Bias Limit B_{R_T}	Precision Limit P_{R_T}	Overall Uncertainty U_{R_T}	
		B_{std} (± lbf)	B_{cf} (± lbf)	B_e (± lbf)	B_{data} (± lbf)	$B_{install}$ (± lbf)	$B_{concept}$ (± lbf)	(± lbf)	(± lbf)	(± lbf)	(± %)
1	4.354	0.0005	0.0550	0.0013	0.0140	0.0002	0.0000	0.057	0.180	0.188	4.33
2	4.318	0.0005	0.0550	0.0013	0.0140	0.0002	0.0000	0.057	0.179	0.188	4.36
3	4.461	0.0005	0.0550	0.0013	0.0140	0.0002	0.0000	0.057	0.180	0.189	4.24
4	9.468	0.0007	0.0550	0.0013	0.0140	0.0004	0.0000	0.057	0.222	0.229	2.42
5	9.698	0.0007	0.0550	0.0013	0.0140	0.0004	0.0000	0.057	0.224	0.231	2.38
6	9.533	0.0007	0.0550	0.0013	0.0140	0.0004	0.0000	0.057	0.223	0.230	2.41
7	13.497	0.0008	0.0550	0.0013	0.0140	0.0005	0.0000	0.057	0.256	0.262	1.94
8	13.215	0.0008	0.0550	0.0013	0.0140	0.0005	0.0000	0.057	0.253	0.259	1.96
9	13.244	0.0008	0.0550	0.0013	0.0140	0.0005	0.0000	0.057	0.253	0.260	1.96
10	7.464	0.0006	0.0550	0.0013	0.0140	0.0003	0.0000	0.057	0.205	0.213	2.86
11	7.466	0.0006	0.0550	0.0013	0.0140	0.0003	0.0000	0.057	0.205	0.213	2.85
12	7.624	0.0006	0.0550	0.0013	0.0140	0.0003	0.0000	0.057	0.207	0.214	2.81
13	7.491	0.0006	0.0550	0.0013	0.0140	0.0003	0.0000	0.057	0.206	0.213	2.85
14	7.437	0.0006	0.0550	0.0013	0.0140	0.0003	0.0000	0.057	0.205	0.213	2.86
15	7.600	0.0006	0.0550	0.0013	0.0140	0.0003	0.0000	0.057	0.207	0.214	2.82
16	7.393	0.0006	0.0550	0.0013	0.0140	0.0003	0.0000	0.057	0.205	0.213	2.87
17	7.410	0.0006	0.0550	0.0013	0.0140	0.0003	0.0000	0.057	0.205	0.213	2.87
18	7.600	0.0006	0.0550	0.0013	0.0140	0.0003	0.0000	0.057	0.207	0.214	2.82
19	7.521	0.0006	0.0550	0.0013	0.0140	0.0003	0.0000	0.057	0.206	0.214	2.84
20	7.549	0.0006	0.0550	0.0013	0.0140	0.0003	0.0000	0.057	0.206	0.214	2.83
21	7.580	0.0006	0.0550	0.0013	0.0140	0.0003	0.0000	0.057	0.206	0.214	2.82
22	7.365	0.0006	0.0550	0.0013	0.0140	0.0003	0.0000	0.057	0.205	0.212	2.88
23	7.437	0.0006	0.0550	0.0013	0.0140	0.0003	0.0000	0.057	0.205	0.213	2.86
24	7.324	0.0006	0.0550	0.0013	0.0140	0.0003	0.0000	0.057	0.204	0.212	2.89
25	7.380	0.0006	0.0550	0.0013	0.0140	0.0003	0.0000	0.057	0.205	0.212	2.88
26	7.543	0.0006	0.0550	0.0013	0.0140	0.0003	0.0000	0.057	0.206	0.214	2.83
27	7.642	0.0006	0.0550	0.0013	0.0140	0.0003	0.0000	0.057	0.207	0.215	2.81
28	7.614	0.0006	0.0550	0.0013	0.0140	0.0003	0.0000	0.057	0.207	0.214	2.81
29	7.568	0.0006	0.0550	0.0013	0.0140	0.0003	0.0000	0.057	0.206	0.214	2.83
30	7.421	0.0006	0.0550	0.0013	0.0140	0.0003	0.0000	0.057	0.205	0.213	2.87
31	26.309	0.0011	0.0550	0.0013	0.0140	0.0010	0.0000	0.057	0.362	0.366	1.39
32	26.070	0.0011	0.0550	0.0013	0.0140	0.0010	0.0000	0.057	0.360	0.364	1.40
33	26.242	0.0011	0.0550	0.0013	0.0140	0.0010	0.0000	0.057	0.361	0.366	1.39
34	26.722	0.0012	0.0550	0.0013	0.0140	0.0010	0.0000	0.057	0.365	0.370	1.38
35	5.317	0.0005	0.0550	0.0013	0.0140	0.0002	0.0000	0.057	0.188	0.196	3.69
36	5.169	0.0005	0.0550	0.0013	0.0140	0.0002	0.0000	0.057	0.186	0.195	3.77
37	5.377	0.0005	0.0550	0.0013	0.0140	0.0002	0.0000	0.057	0.188	0.196	3.65
38	8.513	0.0007	0.0550	0.0013	0.0140	0.0003	0.0000	0.057	0.214	0.222	2.60
39	8.418	0.0007	0.0550	0.0013	0.0140	0.0003	0.0000	0.057	0.213	0.221	2.62
40	8.551	0.0007	0.0550	0.0013	0.0140	0.0003	0.0000	0.057	0.214	0.222	2.59
41	14.730	0.0009	0.0550	0.0013	0.0140	0.0006	0.0000	0.057	0.266	0.272	1.84
42	14.764	0.0009	0.0550	0.0013	0.0140	0.0006	0.0000	0.057	0.266	0.272	1.84

Table A8. Uncertainty analysis of measured model total resistance (U_{RT}), resistance test, continued.

Data Spot No.	Model Total Resistance R_T (lbf)	Elemental Bias Errors						Bias Limit B_{R_T}	Precision Limit P_{R_T}	Overall Uncertainty U_{R_T}	
		B_{std} (± lbf)	B_{cf} (± lbf)	B_e (± lbf)	B_{data} (± lbf)	$B_{install}$ (± lbf)	$B_{concept}$ (± lbf)	(± lbf)	(± lbf)	(± lbf)	(± %)
43	14.708	0.0009	0.0550	0.0013	0.0140	0.0006	0.0000	0.057	0.266	0.272	1.85
44	12.047	0.0008	0.0550	0.0013	0.0140	0.0005	0.0000	0.057	0.243	0.250	2.08
45	12.015	0.0008	0.0550	0.0013	0.0140	0.0005	0.0000	0.057	0.243	0.250	2.08
46	11.879	0.0008	0.0550	0.0013	0.0140	0.0005	0.0000	0.057	0.242	0.249	2.09
47	11.990	0.0008	0.0550	0.0013	0.0140	0.0005	0.0000	0.057	0.243	0.250	2.08
48	12.020	0.0008	0.0550	0.0013	0.0140	0.0005	0.0000	0.057	0.243	0.250	2.08
49	12.074	0.0008	0.0550	0.0013	0.0140	0.0005	0.0000	0.057	0.244	0.250	2.07
50	11.893	0.0008	0.0550	0.0013	0.0140	0.0005	0.0000	0.057	0.242	0.249	2.09
51	11.941	0.0008	0.0550	0.0013	0.0140	0.0005	0.0000	0.057	0.243	0.249	2.09
52	12.040	0.0008	0.0550	0.0013	0.0140	0.0005	0.0000	0.057	0.243	0.250	2.08
53	12.090	0.0008	0.0550	0.0013	0.0140	0.0005	0.0000	0.057	0.244	0.250	2.07
54	11.854	0.0008	0.0550	0.0013	0.0140	0.0005	0.0000	0.057	0.242	0.248	2.10
55	11.640	0.0008	0.0550	0.0013	0.0140	0.0004	0.0000	0.057	0.240	0.247	2.12
56	11.951	0.0008	0.0550	0.0013	0.0140	0.0005	0.0000	0.057	0.243	0.249	2.09
57	11.717	0.0008	0.0550	0.0013	0.0140	0.0004	0.0000	0.057	0.241	0.247	2.11
58	11.927	0.0008	0.0550	0.0013	0.0140	0.0005	0.0000	0.057	0.242	0.249	2.09
59	11.866	0.0008	0.0550	0.0013	0.0140	0.0005	0.0000	0.057	0.242	0.249	2.09
60	11.965	0.0008	0.0550	0.0013	0.0140	0.0005	0.0000	0.057	0.243	0.249	2.08
61	12.061	0.0008	0.0550	0.0013	0.0140	0.0005	0.0000	0.057	0.244	0.250	2.07
62	12.018	0.0008	0.0550	0.0013	0.0140	0.0005	0.0000	0.057	0.243	0.250	2.08
63	12.105	0.0008	0.0550	0.0013	0.0140	0.0005	0.0000	0.057	0.244	0.250	2.07
64	21.021	0.0010	0.0550	0.0013	0.0140	0.0008	0.0000	0.057	0.318	0.323	1.54
65	21.198	0.0010	0.0550	0.0013	0.0140	0.0008	0.0000	0.057	0.319	0.324	1.53
66	21.395	0.0010	0.0550	0.0013	0.0140	0.0008	0.0000	0.057	0.321	0.326	1.52
67	21.398	0.0010	0.0550	0.0013	0.0140	0.0008	0.0000	0.057	0.321	0.326	1.52
68	21.765	0.0010	0.0550	0.0013	0.0140	0.0008	0.0000	0.057	0.324	0.329	1.51
69	6.468	0.0006	0.0550	0.0013	0.0140	0.0002	0.0000	0.057	0.197	0.205	3.17
70	6.515	0.0006	0.0550	0.0013	0.0140	0.0002	0.0000	0.057	0.198	0.206	3.15
71	6.535	0.0006	0.0550	0.0013	0.0140	0.0002	0.0000	0.057	0.198	0.206	3.15
72	10.779	0.0007	0.0550	0.0013	0.0140	0.0004	0.0000	0.057	0.233	0.240	2.22
73	10.737	0.0007	0.0550	0.0013	0.0140	0.0004	0.0000	0.057	0.233	0.239	2.23
74	10.803	0.0007	0.0550	0.0013	0.0140	0.0004	0.0000	0.057	0.233	0.240	2.22
75	18.452	0.0010	0.0550	0.0013	0.0140	0.0007	0.0000	0.057	0.297	0.302	1.64
76	18.373	0.0010	0.0550	0.0013	0.0140	0.0007	0.0000	0.057	0.296	0.301	1.64
77	18.450	0.0010	0.0550	0.0013	0.0140	0.0007	0.0000	0.057	0.297	0.302	1.64
78	18.538	0.0010	0.0550	0.0013	0.0140	0.0007	0.0000	0.057	0.297	0.303	1.63
79	4.574	0.0005	0.0550	0.0013	0.0140	0.0002	0.0000	0.057	0.181	0.190	4.16
80	4.531	0.0005	0.0550	0.0013	0.0140	0.0002	0.0000	0.057	0.181	0.190	4.19
81	6.401	0.0006	0.0550	0.0013	0.0140	0.0002	0.0000	0.057	0.197	0.205	3.20
82	6.415	0.0006	0.0550	0.0013	0.0140	0.0002	0.0000	0.057	0.197	0.205	3.19
83	8.459	0.0007	0.0550	0.0013	0.0140	0.0003	0.0000	0.057	0.214	0.221	2.61
84	8.646	0.0007	0.0550	0.0013	0.0140	0.0003	0.0000	0.057	0.215	0.223	2.57
85	**16.469**	**0.0009**	**0.0550**	**0.0013**	**0.0140**	**0.0006**	**0.0000**	**0.057**	**0.280**	**0.286**	**1.74**

Table A8. Uncertainty analysis of measured model total resistance (U_{RT}), resistance test, continued.

Data Spot No.	Model Total Resistance R_T (lbf)	Elemental Bias Errors						Bias Limit B_{R_T}	Precision Limit P_{R_T}	Overall Uncertainty U_{R_T}	
		B_{std} (± lbf)	B_{cf} (± lbf)	B_e (± lbf)	B_{data} (± lbf)	$B_{install}$ (± lbf)	$B_{concept}$ (± lbf)	(± lbf)	(± lbf)	(± lbf)	(± %)
86	16.482	0.0009	0.0550	0.0013	0.0140	0.0006	0.0000	0.057	0.280	0.286	1.74
87	16.687	0.0009	0.0550	0.0013	0.0140	0.0006	0.0000	0.057	0.282	0.288	1.72
88	16.695	0.0009	0.0550	0.0013	0.0140	0.0006	0.0000	0.057	0.282	0.288	1.72
89	16.838	0.0009	0.0550	0.0013	0.0140	0.0006	0.0000	0.057	0.283	0.289	1.72
90	16.686	0.0009	0.0550	0.0013	0.0140	0.0006	0.0000	0.057	0.282	0.288	1.72
91	16.570	0.0009	0.0550	0.0013	0.0140	0.0006	0.0000	0.057	0.281	0.287	1.73
92	16.431	0.0009	0.0550	0.0013	0.0140	0.0006	0.0000	0.057	0.280	0.286	1.74
93	16.337	0.0009	0.0550	0.0013	0.0140	0.0006	0.0000	0.057	0.279	0.285	1.74
94	16.537	0.0009	0.0550	0.0013	0.0140	0.0006	0.0000	0.057	0.281	0.286	1.73
95	16.541	0.0009	0.0550	0.0013	0.0140	0.0006	0.0000	0.057	0.281	0.286	1.73
96	16.584	0.0009	0.0550	0.0013	0.0140	0.0006	0.0000	0.057	0.281	0.287	1.73
97	16.510	0.0009	0.0550	0.0013	0.0140	0.0006	0.0000	0.057	0.281	0.286	1.73
98	16.656	0.0009	0.0550	0.0013	0.0140	0.0006	0.0000	0.057	0.282	0.287	1.73
99	16.673	0.0009	0.0550	0.0013	0.0140	0.0006	0.0000	0.057	0.282	0.288	1.72
100	16.531	0.0009	0.0550	0.0013	0.0140	0.0006	0.0000	0.057	0.281	0.286	1.73
101	16.296	0.0009	0.0550	0.0013	0.0140	0.0006	0.0000	0.057	0.279	0.284	1.75
102	16.608	0.0009	0.0550	0.0013	0.0140	0.0006	0.0000	0.057	0.281	0.287	1.73
103	16.852	0.0009	0.0550	0.0013	0.0140	0.0006	0.0000	0.057	0.283	0.289	1.72
104	16.598	0.0009	0.0550	0.0013	0.0140	0.0006	0.0000	0.057	0.281	0.287	1.73
105	16.615	0.0009	0.0550	0.0013	0.0140	0.0006	0.0000	0.057	0.281	0.287	1.73
106	16.572	0.0009	0.0550	0.0013	0.0140	0.0006	0.0000	0.057	0.281	0.287	1.73
107	16.553	0.0009	0.0550	0.0013	0.0140	0.0006	0.0000	0.057	0.281	0.287	1.73
108	13.369	0.0008	0.0550	0.0013	0.0140	0.0005	0.0000	0.057	0.254	0.261	1.95
109	13.400	0.0008	0.0550	0.0013	0.0140	0.0005	0.0000	0.057	0.255	0.261	1.95
110	26.428	0.0011	0.0550	0.0013	0.0140	0.0010	0.0000	0.057	0.363	0.367	1.39
111	26.489	0.0011	0.0550	0.0013	0.0140	0.0010	0.0000	0.057	0.363	0.368	1.39
112	5.362	0.0005	0.0550	0.0013	0.0140	0.0002	0.0000	0.057	0.188	0.196	3.66
113	5.358	0.0005	0.0550	0.0013	0.0140	0.0002	0.0000	0.057	0.188	0.196	3.66
114	9.677	0.0007	0.0550	0.0013	0.0140	0.0004	0.0000	0.057	0.224	0.231	2.39
115	9.571	0.0007	0.0550	0.0013	0.0140	0.0004	0.0000	0.057	0.223	0.230	2.40
116	21.386	0.0010	0.0550	0.0013	0.0140	0.0008	0.0000	0.057	0.321	0.326	1.52
117	21.269	0.0010	0.0550	0.0013	0.0140	0.0008	0.0000	0.057	0.320	0.325	1.53
118	10.536	0.0007	0.0550	0.0013	0.0140	0.0004	0.0000	0.057	0.231	0.238	2.26
119	10.829	0.0007	0.0550	0.0013	0.0140	0.0004	0.0000	0.057	0.233	0.240	2.22
120	14.755	0.0009	0.0550	0.0013	0.0140	0.0006	0.0000	0.057	0.266	0.272	1.84
121	14.777	0.0009	0.0550	0.0013	0.0140	0.0006	0.0000	0.057	0.266	0.272	1.84
122	14.831	0.0009	0.0550	0.0013	0.0140	0.0006	0.0000	0.057	0.267	0.273	1.84
123	18.206	0.0010	0.0550	0.0013	0.0140	0.0007	0.0000	0.057	0.295	0.300	1.65
124	18.229	0.0010	0.0550	0.0013	0.0140	0.0007	0.0000	0.057	0.295	0.300	1.65
125	23.482	0.0011	0.0550	0.0013	0.0140	0.0009	0.0000	0.057	0.338	0.343	1.46
126	23.308	0.0011	0.0550	0.0013	0.0140	0.0009	0.0000	0.057	0.337	0.342	1.47
127	23.697	0.0011	0.0550	0.0013	0.0140	0.0009	0.0000	0.057	0.340	0.345	1.46

Table A9. Uncertainty analysis of calculated coefficient of total resistance (U_{C_T}), resistance test.

Data Spot #	Model Speed V (ft/sec)	Total Res. R_T (lbf)	C_T (10^{-3})	$\delta C_T/\delta R_T$ (1/lbf)	$\delta C_T/\delta\rho$ 1/(lbfs^2/ft^4)	$\delta C_T/\delta V$ 1/(ft/s)	B_{R_T} (± lbf)	B_ρ (± lbfs^2/ft^4)	B_V (± ft/s)	B_{C_T} ±(10^{-5})	P_{R_T} (± lbf)	P_V (± ft/s)	P_{C_T} ±(10^{-5})	U_{C_T} ±(10^{-5})	U_{C_T} ±%
1	3.359	4.354	3.42	0.0008	-0.0018	-0.0020	0.057	0.007	0.0009	4.62	0.180	0.0019	14.09	14.83	4.34
2	3.359	4.318	3.39	0.0008	-0.0017	-0.0020	0.057	0.007	0.0009	4.62	0.179	0.0019	14.07	14.81	4.37
3	3.359	4.461	3.50	0.0008	-0.0018	-0.0021	0.057	0.007	0.0009	4.63	0.180	0.0019	14.16	14.90	4.26
4	5.016	9.468	3.33	0.0004	-0.0017	-0.0013	0.057	0.007	0.0013	2.34	0.222	0.0034	7.82	8.17	2.45
5	5.018	9.698	3.41	0.0004	-0.0018	-0.0014	0.057	0.007	0.0013	2.35	0.224	0.0034	7.89	8.23	2.41
6	5.017	9.533	3.35	0.0004	-0.0017	-0.0013	0.057	0.007	0.0013	2.34	0.223	0.0034	7.84	8.18	2.44
7	6.019	13.497	3.30	0.0002	-0.0017	-0.0011	0.057	0.007	0.0015	1.84	0.256	0.0043	6.26	6.52	1.98
8	6.021	13.215	3.23	0.0002	-0.0017	-0.0011	0.057	0.007	0.0015	1.82	0.253	0.0043	6.20	6.46	2.00
9	6.018	13.244	3.24	0.0002	-0.0017	-0.0011	0.057	0.007	0.0015	1.82	0.253	0.0043	6.21	6.47	2.00
10	4.366	7.464	3.47	0.0005	-0.0018	-0.0016	0.057	0.007	0.0011	2.92	0.205	0.0028	9.55	9.99	2.88
11	4.365	7.466	3.47	0.0005	-0.0018	-0.0016	0.057	0.007	0.0011	2.93	0.205	0.0028	9.55	9.99	2.88
12	4.365	7.624	3.54	0.0005	-0.0018	-0.0016	0.057	0.007	0.0011	2.94	0.207	0.0028	9.61	10.05	2.84
13	4.368	7.491	3.47	0.0005	-0.0018	-0.0016	0.057	0.007	0.0011	2.92	0.206	0.0028	9.55	9.99	2.87
14	4.367	7.437	3.45	0.0005	-0.0018	-0.0016	0.057	0.007	0.0011	2.92	0.205	0.0028	9.53	9.97	2.89
15	4.368	7.600	3.53	0.0005	-0.0018	-0.0016	0.057	0.007	0.0011	2.93	0.207	0.0028	9.59	10.03	2.85
16	4.367	7.393	3.43	0.0005	-0.0018	-0.0016	0.057	0.007	0.0011	2.92	0.205	0.0028	9.52	9.95	2.90
17	4.367	7.410	3.44	0.0005	-0.0018	-0.0016	0.057	0.007	0.0011	2.92	0.205	0.0028	9.52	9.96	2.90
18	4.369	7.600	3.52	0.0005	-0.0018	-0.0016	0.057	0.007	0.0011	2.93	0.207	0.0028	9.59	10.02	2.85
19	4.366	7.521	3.49	0.0005	-0.0018	-0.0016	0.057	0.007	0.0011	2.93	0.206	0.0028	9.57	10.01	2.87
20	4.366	7.549	3.50	0.0005	-0.0018	-0.0016	0.057	0.007	0.0011	2.93	0.206	0.0028	9.58	10.02	2.86
21	4.366	7.580	3.52	0.0005	-0.0018	-0.0016	0.057	0.007	0.0011	2.93	0.206	0.0028	9.59	10.03	2.85
22	4.368	7.365	3.42	0.0005	-0.0018	-0.0016	0.057	0.007	0.0011	2.91	0.205	0.0028	9.50	9.94	2.91
23	4.368	7.437	3.45	0.0005	-0.0018	-0.0016	0.057	0.007	0.0011	2.92	0.205	0.0028	9.53	9.97	2.89
24	4.367	7.324	3.40	0.0005	-0.0018	-0.0016	0.057	0.007	0.0011	2.91	0.204	0.0028	9.49	9.93	2.92
25	4.368	7.380	3.42	0.0005	-0.0018	-0.0016	0.057	0.007	0.0011	2.91	0.205	0.0028	9.51	9.94	2.90
26	4.366	7.543	3.50	0.0005	-0.0018	-0.0016	0.057	0.007	0.0011	2.93	0.206	0.0028	9.58	10.02	2.86
27	4.366	7.642	3.55	0.0005	-0.0018	-0.0016	0.057	0.007	0.0011	2.94	0.207	0.0028	9.62	10.06	2.83
28	4.364	7.614	3.54	0.0005	-0.0018	-0.0016	0.057	0.007	0.0011	2.94	0.207	0.0028	9.61	10.05	2.84
29	4.367	7.568	3.51	0.0005	-0.0018	-0.0016	0.057	0.007	0.0011	2.93	0.206	0.0028	9.58	10.02	2.85
30	4.366	7.421	3.45	0.0005	-0.0018	-0.0016	0.057	0.007	0.0011	2.92	0.205	0.0028	9.53	9.97	2.89
31	7.673	26.309	3.95	0.0002	-0.0020	-0.0010	0.057	0.007	0.0020	1.68	0.362	0.0058	5.47	5.72	1.45
32	7.673	26.070	3.92	0.0002	-0.0020	-0.0010	0.057	0.007	0.0020	1.67	0.360	0.0058	5.44	5.69	1.45
33	7.673	26.242	3.94	0.0002	-0.0020	-0.0010	0.057	0.007	0.0020	1.67	0.361	0.0058	5.47	5.72	1.45
34	7.672	26.722	4.02	0.0002	-0.0021	-0.0010	0.057	0.007	0.0019	1.70	0.365	0.0058	5.53	5.78	1.44
35	3.687	5.317	3.46	0.0007	-0.0018	-0.0019	0.057	0.007	0.0009	3.91	0.188	0.0022	12.22	12.83	3.71
36	3.689	5.169	3.36	0.0007	-0.0017	-0.0018	0.057	0.007	0.0009	3.89	0.186	0.0022	12.13	12.73	3.79
37	3.688	5.377	3.50	0.0007	-0.0018	-0.0019	0.057	0.007	0.0009	3.91	0.188	0.0022	12.25	12.85	3.67
38	4.686	8.513	3.43	0.0004	-0.0018	-0.0015	0.057	0.007	0.0012	2.61	0.214	0.0031	8.64	9.03	2.63
39	4.688	8.418	3.39	0.0004	-0.0018	-0.0014	0.057	0.007	0.0012	2.60	0.213	0.0031	8.60	8.99	2.65
40	4.689	8.551	3.44	0.0004	-0.0018	-0.0015	0.057	0.007	0.0012	2.61	0.214	0.0031	8.64	9.03	2.62
41	6.340	14.730	3.24	0.0002	-0.0017	-0.0010	0.057	0.007	0.0016	1.72	0.266	0.0046	5.87	6.12	1.89
42	6.342	14.764	3.25	0.0002	-0.0017	-0.0010	0.057	0.007	0.0016	1.72	0.266	0.0046	5.87	6.12	1.88
43	6.340	14.708	3.24	0.0002	-0.0017	-0.0010	0.057	0.007	0.0016	1.72	0.266	0.0046	5.87	6.11	1.89
44	5.688	12.047	3.30	0.0003	-0.0017	-0.0012	0.057	0.007	0.0014	1.96	0.243	0.0040	6.68	6.96	2.11
45	5.686	12.015	3.29	0.0003	-0.0017	-0.0012	0.057	0.007	0.0014	1.96	0.243	0.0040	6.67	6.96	2.12
46	5.685	11.879	3.25	0.0003	-0.0017	-0.0011	0.057	0.007	0.0014	1.96	0.242	0.0040	6.65	6.93	2.13
47	5.689	11.990	3.28	0.0003	-0.0017	-0.0012	0.057	0.007	0.0014	1.96	0.243	0.0040	6.66	6.94	2.12
48	5.691	12.020	3.28	0.0003	-0.0017	-0.0012	0.057	0.007	0.0014	1.96	0.243	0.0040	6.66	6.95	2.11

Table A9. Uncertainty analysis of calculated coefficient of total resistance (U_{C_T}), resistance test, continued.

Data Spot #	Model Speed V (ft/sec)	Total Res. R_T (lbf)	C_T (10^{-3})	$\delta C_T/\delta R_T$ (1/lbf)	$\delta C_T/\delta\rho$ 1/(lbfs^2/ft^4)	$\delta C_T/\delta V$ 1/(ft/s)	B_{R_T} (± lbf)	B_ρ (± lbfs^2/ft^4)	B_V (± ft/s)	B_{C_T} ±(10^{-5})	P_{R_T} (± lbf)	P_V (± ft/s)	P_{C_T} ±(10^{-5})	U_{C_T} ±(10^{-5})	U_{C_T} ±%
49	5.690	12.074	3.30	0.0003	-0.0017	-0.0012	0.057	0.007	0.0014	1.96	0.244	0.0040	6.68	6.96	2.11
50	5.691	11.893	3.25	0.0003	-0.0017	-0.0011	0.057	0.007	0.0014	1.95	0.242	0.0040	6.63	6.92	2.13
51	5.688	11.941	3.27	0.0003	-0.0017	-0.0011	0.057	0.007	0.0014	1.96	0.243	0.0040	6.65	6.93	2.12
52	5.692	12.040	3.29	0.0003	-0.0017	-0.0012	0.057	0.007	0.0014	1.96	0.243	0.0040	6.67	6.95	2.11
53	5.690	12.090	3.30	0.0003	-0.0017	-0.0012	0.057	0.007	0.0014	1.97	0.244	0.0040	6.68	6.96	2.11
54	5.687	11.854	3.24	0.0003	-0.0017	-0.0011	0.057	0.007	0.0014	1.95	0.242	0.0040	6.63	6.92	2.13
55	5.690	11.640	3.18	0.0003	-0.0016	-0.0011	0.057	0.007	0.0014	1.94	0.240	0.0040	6.58	6.86	2.16
56	5.688	11.951	3.27	0.0003	-0.0017	-0.0011	0.057	0.007	0.0014	1.96	0.243	0.0040	6.65	6.94	2.12
57	5.690	11.717	3.20	0.0003	-0.0017	-0.0011	0.057	0.007	0.0014	1.94	0.241	0.0040	6.60	6.88	2.15
58	5.690	11.927	3.26	0.0003	-0.0017	-0.0011	0.057	0.007	0.0014	1.96	0.242	0.0040	6.64	6.93	2.12
59	5.690	11.866	3.24	0.0003	-0.0017	-0.0011	0.057	0.007	0.0014	1.95	0.242	0.0040	6.63	6.91	2.13
60	5.693	11.965	3.27	0.0003	-0.0017	-0.0011	0.057	0.007	0.0014	1.96	0.243	0.0040	6.65	6.93	2.12
61	5.692	12.061	3.29	0.0003	-0.0017	-0.0012	0.057	0.007	0.0014	1.96	0.244	0.0040	6.67	6.95	2.11
62	5.693	12.018	3.28	0.0003	-0.0017	-0.0012	0.057	0.007	0.0014	1.96	0.243	0.0040	6.66	6.94	2.11
63	5.692	12.105	3.31	0.0003	-0.0017	-0.0012	0.057	0.007	0.0014	1.97	0.244	0.0040	6.68	6.96	2.11
64	7.342	21.021	3.45	0.0002	-0.0018	-0.0009	0.057	0.007	0.0019	1.57	0.318	0.0055	5.25	5.48	1.59
65	7.343	21.198	3.48	0.0002	-0.0018	-0.0009	0.057	0.007	0.0019	1.58	0.319	0.0055	5.27	5.50	1.58
66	7.344	21.395	3.51	0.0002	-0.0018	-0.0010	0.057	0.007	0.0019	1.58	0.321	0.0055	5.30	5.53	1.57
67	7.342	21.398	3.51	0.0002	-0.0018	-0.0010	0.057	0.007	0.0019	1.59	0.321	0.0055	5.30	5.53	1.57
68	7.342	21.765	3.57	0.0002	-0.0018	-0.0010	0.057	0.007	0.0019	1.60	0.324	0.0055	5.35	5.58	1.56
69	4.019	6.468	3.54	0.0005	-0.0018	-0.0018	0.057	0.007	0.0010	3.37	0.197	0.0025	10.81	11.32	3.20
70	4.019	6.515	3.57	0.0005	-0.0018	-0.0018	0.057	0.007	0.0010	3.37	0.198	0.0025	10.83	11.35	3.18
71	4.018	6.535	3.58	0.0005	-0.0018	-0.0018	0.057	0.007	0.0010	3.38	0.198	0.0025	10.85	11.36	3.17
72	5.341	10.779	3.34	0.0003	-0.0017	-0.0013	0.057	0.007	0.0014	2.14	0.233	0.0037	7.24	7.55	2.26
73	5.342	10.737	3.33	0.0003	-0.0017	-0.0012	0.057	0.007	0.0014	2.14	0.233	0.0037	7.23	7.54	2.26
74	5.339	10.803	3.35	0.0003	-0.0017	-0.0013	0.057	0.007	0.0014	2.15	0.233	0.0037	7.25	7.56	2.26
75	7.009	18.452	3.32	0.0002	-0.0017	-0.0009	0.057	0.007	0.0018	1.59	0.297	0.0052	5.37	5.60	1.68
76	7.009	18.373	3.31	0.0002	-0.0017	-0.0009	0.057	0.007	0.0018	1.58	0.296	0.0052	5.36	5.58	1.69
77	7.009	18.450	3.32	0.0002	-0.0017	-0.0009	0.057	0.007	0.0018	1.59	0.297	0.0052	5.37	5.60	1.68
78	7.009	18.538	3.34	0.0002	-0.0017	-0.0010	0.057	0.007	0.0018	1.59	0.297	0.0052	5.38	5.61	1.68
79	3.360	4.574	3.59	0.0008	-0.0019	-0.0021	0.057	0.007	0.0009	4.64	0.181	0.0019	14.23	14.96	4.17
80	3.359	4.531	3.55	0.0008	-0.0018	-0.0021	0.057	0.007	0.0009	4.64	0.181	0.0019	14.21	14.95	4.21
81	4.020	6.401	3.51	0.0005	-0.0018	-0.0017	0.057	0.007	0.0010	3.36	0.197	0.0025	10.77	11.29	3.22
82	4.018	6.415	3.52	0.0005	-0.0018	-0.0018	0.057	0.007	0.0010	3.37	0.197	0.0025	10.79	11.30	3.21
83	4.695	8.459	3.40	0.0004	-0.0018	-0.0014	0.057	0.007	0.0012	2.59	0.214	0.0031	8.59	8.97	2.64
84	4.697	8.646	3.47	0.0004	-0.0018	-0.0015	0.057	0.007	0.0012	2.61	0.215	0.0031	8.65	9.03	2.60
85	**6.681**	**16.469**	**3.27**	**0.0002**	**-0.0017**	**-0.0010**	**0.057**	**0.007**	**0.0017**	**1.64**	**0.280**	**0.0049**	**5.58**	**5.81**	**1.78**
86	6.681	16.482	3.27	0.0002	-0.0017	-0.0010	0.057	0.007	0.0017	1.64	0.280	0.0049	5.58	5.81	1.78
87	6.682	16.687	3.31	0.0002	-0.0017	-0.0010	0.057	0.007	0.0017	1.65	0.282	0.0049	5.61	5.85	1.77
88	6.680	16.695	3.31	0.0002	-0.0017	-0.0010	0.057	0.007	0.0017	1.65	0.282	0.0049	5.62	5.85	1.77
89	6.682	16.838	3.34	0.0002	-0.0017	-0.0010	0.057	0.007	0.0017	1.66	0.283	0.0049	5.64	5.88	1.76
90	6.684	16.686	3.31	0.0002	-0.0017	-0.0010	0.057	0.007	0.0017	1.65	0.282	0.0049	5.61	5.85	1.77
91	6.684	16.570	3.28	0.0002	-0.0017	-0.0010	0.057	0.007	0.0017	1.64	0.281	0.0049	5.59	5.82	1.77
92	6.684	16.431	3.25	0.0002	-0.0017	-0.0010	0.057	0.007	0.0017	1.64	0.280	0.0049	5.57	5.80	1.78
93	6.683	16.337	3.24	0.0002	-0.0017	-0.0010	0.057	0.007	0.0017	1.63	0.279	0.0049	5.55	5.79	1.79
94	6.686	16.537	3.27	0.0002	-0.0017	-0.0010	0.057	0.007	0.0017	1.64	0.281	0.0049	5.58	5.82	1.78
95	6.686	16.541	3.27	0.0002	-0.0017	-0.0010	0.057	0.007	0.0017	1.64	0.281	0.0049	5.58	5.82	1.78
96	6.684	16.584	3.29	0.0002	-0.0017	-0.0010	0.057	0.007	0.0017	1.64	0.281	0.0049	5.59	5.83	1.77

Table A9. Uncertainty analysis of calculated coefficient of total resistance (U_{C_T}), resistance test, continued.

Data Spot #	Model Speed V (ft/sec)	Total Res. R_T (lbf)	C_T (10^{-3})	$\delta C_T/\delta R_T$ (1/lbf)	$\delta C_T/\delta\rho$ 1/(lbfs^2/ft^4)	$\delta C_T/\delta V$ 1/(ft/s)	B_{R_T} (± lbf)	B_ρ (± lbfs^2/ft^4)	B_V (± ft/s)	B_{C_T} ±(10^{-5})	P_{R_T} (± lbf)	P_V (± ft/s)	P_{C_T} ±(10^{-5})	U_{C_T} ±(10^{-5})	U_{C_T} ±%
97	6.684	16.510	3.27	0.0002	-0.0017	-0.0010	0.057	0.007	0.0017	1.64	0.281	0.0049	5.58	5.81	1.78
98	6.685	16.656	3.30	0.0002	-0.0017	-0.0010	0.057	0.007	0.0017	1.65	0.282	0.0049	5.60	5.84	1.77
99	6.687	16.673	3.30	0.0002	-0.0017	-0.0010	0.057	0.007	0.0017	1.65	0.282	0.0049	5.60	5.84	1.77
100	6.687	16.531	3.27	0.0002	-0.0017	-0.0010	0.057	0.007	0.0017	1.64	0.281	0.0049	5.58	5.81	1.78
101	6.687	16.296	3.23	0.0002	-0.0017	-0.0010	0.057	0.007	0.0017	1.63	0.279	0.0049	5.54	5.77	1.79
102	6.687	16.608	3.29	0.0002	-0.0017	-0.0010	0.057	0.007	0.0017	1.64	0.281	0.0049	5.59	5.83	1.77
103	6.686	16.852	3.34	0.0002	-0.0017	-0.0010	0.057	0.007	0.0017	1.66	0.283	0.0049	5.63	5.87	1.76
104	6.687	16.598	3.28	0.0002	-0.0017	-0.0010	0.057	0.007	0.0017	1.64	0.281	0.0049	5.59	5.82	1.77
105	6.687	16.615	3.29	0.0002	-0.0017	-0.0010	0.057	0.007	0.0017	1.64	0.281	0.0049	5.59	5.83	1.77
106	6.686	16.572	3.28	0.0002	-0.0017	-0.0010	0.057	0.007	0.0017	1.64	0.281	0.0049	5.59	5.82	1.77
107	6.686	16.553	3.28	0.0002	-0.0017	-0.0010	0.057	0.007	0.0017	1.64	0.281	0.0049	5.58	5.82	1.78
108	6.017	13.369	3.27	0.0002	-0.0017	-0.0011	0.057	0.007	0.0015	1.83	0.254	0.0043	6.24	6.50	1.99
109	6.017	13.400	3.28	0.0002	-0.0017	-0.0011	0.057	0.007	0.0015	1.83	0.255	0.0043	6.24	6.51	1.99
110	7.671	26.428	3.97	0.0002	-0.0021	-0.0010	0.057	0.007	0.0019	1.68	0.363	0.0058	5.49	5.74	1.45
111	7.668	26.489	3.99	0.0002	-0.0021	-0.0010	0.057	0.007	0.0019	1.69	0.363	0.0058	5.50	5.76	1.44
112	3.689	5.362	3.49	0.0007	-0.0018	-0.0019	0.057	0.007	0.0009	3.91	0.188	0.0022	12.23	12.84	3.68
113	3.689	5.358	3.48	0.0007	-0.0018	-0.0019	0.057	0.007	0.0009	3.90	0.188	0.0022	12.23	12.84	3.68
114	5.012	9.677	3.41	0.0004	-0.0018	-0.0014	0.057	0.007	0.0013	2.36	0.224	0.0034	7.90	8.24	2.42
115	5.013	9.571	3.37	0.0004	-0.0017	-0.0013	0.057	0.007	0.0013	2.35	0.223	0.0034	7.86	8.21	2.43
116	7.342	21.386	3.51	0.0002	-0.0018	-0.0010	0.057	0.007	0.0019	1.58	0.321	0.0055	5.30	5.53	1.57
117	7.340	21.269	3.49	0.0002	-0.0018	-0.0010	0.057	0.007	0.0019	1.58	0.320	0.0055	5.28	5.52	1.58
118	5.343	10.536	3.27	0.0003	-0.0017	-0.0012	0.057	0.007	0.0014	2.13	0.231	0.0037	7.17	7.48	2.29
119	5.342	10.829	3.36	0.0003	-0.0017	-0.0013	0.057	0.007	0.0014	2.15	0.233	0.0037	7.25	7.56	2.25
120	6.345	14.755	3.24	0.0002	-0.0017	-0.0010	0.057	0.007	0.0016	1.72	0.266	0.0046	5.87	6.11	1.88
121	6.343	14.777	3.25	0.0002	-0.0017	-0.0010	0.057	0.007	0.0016	1.72	0.266	0.0046	5.87	6.12	1.88
122	6.344	14.831	3.26	0.0002	-0.0017	-0.0010	0.057	0.007	0.0016	1.73	0.267	0.0046	5.88	6.13	1.88
123	7.011	18.206	3.28	0.0002	-0.0017	-0.0009	0.057	0.007	0.0018	1.57	0.295	0.0052	5.33	5.55	1.69
124	7.010	18.229	3.28	0.0002	-0.0017	-0.0009	0.057	0.007	0.0018	1.58	0.295	0.0052	5.33	5.56	1.69
125	7.505	23.482	3.69	0.0002	-0.0019	-0.0010	0.057	0.007	0.0019	1.62	0.338	0.0057	5.35	5.59	1.51
126	7.502	23.308	3.67	0.0002	-0.0019	-0.0010	0.057	0.007	0.0019	1.61	0.337	0.0057	5.33	5.57	1.52
127	7.504	23.697	3.72	0.0002	-0.0019	-0.0010	0.057	0.007	0.0019	1.63	0.340	0.0057	5.38	5.62	1.51

Table A10. Self propulsion test data.

Spot Number	Model Speed: V (ft/sec)	Model Drag: Fd (lbf)	Propeller Shaft Rate: N (RPM)	Propeller Shaft Thrust: T (lbf)	Propeller Shaft Torque: Q (in-lbf)	Corresonding Ship Speed (knots)
128	4.019	1.720	281.3	5.491	10.642	12.066
129	4.020	1.932	281.3	5.488	10.624	12.071
130	6.017	3.282	417.5	11.755	22.835	18.066
131	6.017	3.461	417.5	11.754	22.812	18.066
132	6.017	3.304	417.5	11.767	22.831	18.066
133	4.378	2.143	303.8	6.335	12.016	13.146
134	4.378	2.193	303.8	6.333	12.013	13.146
135	4.378	2.161	303.8	6.346	12.038	13.146
136	4.378	2.133	303.8	6.367	12.111	13.146
137	4.376	2.091	303.8	6.359	12.089	13.141
138	4.376	2.153	303.8	6.360	12.087	13.141
139	4.378	2.105	303.8	6.362	12.087	13.146
140	4.378	2.159	303.8	6.361	12.072	13.146
141	4.378	2.108	303.8	6.359	12.039	13.146
142	4.378	2.053	303.8	6.387	12.112	13.146
143	4.378	2.070	303.8	6.383	12.108	13.146
144	4.378	2.169	303.8	6.382	12.087	13.146
145	4.378	2.114	303.8	6.373	12.093	13.146
146	4.378	2.137	303.8	6.379	12.094	13.146
147	4.378	2.125	303.8	6.375	12.073	13.146
148	4.380	2.110	303.8	6.374	12.096	13.151
149	4.378	2.175	303.7	6.379	12.083	13.146
150	4.380	2.068	303.8	6.399	12.162	13.151
151	4.378	2.116	303.8	6.389	12.107	13.146
152	4.378	2.122	303.8	6.390	12.089	13.146
153	3.377	1.297	234.9	3.764	7.464	10.141
154	3.381	1.329	234.5	3.738	7.383	10.151
155	3.384	1.267	234.1	3.704	7.330	10.161
156	5.014	2.413	348.3	8.122	16.010	15.056
157	5.016	2.450	348.3	8.143	16.033	15.061
158	5.016	2.393	348.3	8.145	16.014	15.061
159	5.706	3.106	394.2	10.364	20.016	17.134
160	5.706	3.230	394.2	10.388	20.053	17.134
161	5.705	3.194	394.2	10.358	19.985	17.129
162	5.705	3.111	394.2	10.387	20.048	17.129
163	5.705	3.168	394.2	10.403	20.066	17.129
164	5.705	3.152	394.2	10.425	20.118	17.129
165	5.705	3.055	394.2	10.440	20.134	17.129
166	5.703	3.125	394.2	10.430	20.117	17.124
167	5.703	3.053	394.3	10.451	20.152	17.124
168	5.705	3.111	394.2	10.448	20.142	17.129

Table A10. Self propulsion test data, continued.

Spot Number	Model Speed: V (ft/sec)	Model Drag: Fd (lbf)	Propeller Shaft Rate: N (RPM)	Propeller Shaft Thrust: T (lbf)	Propeller Shaft Torque: Q (in-lbf)	Corresonding Ship Speed (knots)
169	5.705	3.097	394.2	10.453	20.142	17.129
170	5.705	3.055	394.2	10.450	20.117	17.129
171	5.705	3.073	394.1	10.455	20.131	17.129
172	5.701	3.108	394.2	10.472	20.157	17.119
173	5.703	3.158	394.2	10.476	20.147	17.124
174	3.691	1.673	255.4	4.358	8.717	11.083
175	3.691	1.729	255.4	4.352	8.711	11.083
176	5.344	2.737	370.4	9.147	18.039	16.044
177	5.344	2.693	370.4	9.177	18.067	16.044
178	5.344	2.695	370.4	9.213	18.112	16.044
179	7.674	4.461	588.4	25.788	48.645	23.043
180	7.679	4.664	588.4	25.724	48.551	23.058
181	**6.692**	**4.123**	**469.7**	**14.738**	**28.497**	**20.094**
182	6.692	4.146	469.6	14.797	28.601	20.094
183	6.692	4.112	469.7	14.786	28.570	20.094
184	6.694	4.075	469.7	14.838	28.646	20.099
185	6.696	4.075	469.7	14.828	28.623	20.104
186	6.694	4.074	469.6	14.882	28.702	20.099
187	6.692	4.103	469.7	14.913	28.754	20.094
188	6.692	4.148	469.7	14.851	28.610	20.094
189	6.692	3.988	469.6	14.855	28.628	20.094
190	6.694	4.062	469.6	14.860	28.628	20.099
191	6.696	4.063	469.6	14.845	28.593	20.104
192	6.692	4.054	469.6	14.878	28.651	20.094
193	6.694	3.960	469.6	14.819	28.532	20.099
194	7.013	4.066	496.5	16.584	32.383	21.056
195	7.014	4.076	496.4	16.607	32.422	21.062
196	7.013	4.129	496.4	16.634	32.422	21.056
197	7.344	4.142	536.1	20.153	38.824	22.050
198	7.345	4.426	535.2	19.999	38.574	22.055
199	4.685	2.320	326.0	7.132	14.101	14.068
200	4.687	2.413	326.0	7.111	14.042	14.073
201	4.687	2.259	326.0	7.111	14.058	14.073
202	6.344	3.202	448.1	13.643	26.557	19.050
203	6.344	3.219	448.1	13.636	26.554	19.050
204	6.020	3.438	415.5	11.441	22.524	18.077
205	6.019	3.473	415.4	11.459	22.537	18.072
206	6.020	3.481	415.7	11.449	22.521	18.077
207	6.344	3.726	440.4	12.835	25.284	19.050
208	6.344	3.761	440.4	12.897	25.355	19.050
209	6.346	3.587	440.5	12.967	25.480	19.055

Table A11. Calculation of precision limit for measured model speed (P_V) and tow force (P_{FD}) and propeller shaft rate (P_N), thrust (P_T) and torque (P_Q), self propulsion test, 13 knot ship speed.

Spot Index i = 1,N	Test Spot Number	Ship Speed (knots)	Model Speed: V (ft/sec)	Model Tow Force: F_D (lbf)	Propeller Shaft Rate: N (RPM)	Propeller Shaft Thrust: T (lbf)	Propeller Shaft Torque: Q (in-lbf)
1	133	13.15	4.378	2.143	303.80	6.335	12.016
2	134	13.15	4.378	2.193	303.80	6.333	12.013
3	135	13.15	4.378	2.161	303.80	6.346	12.038
4	136	13.15	4.378	2.133	303.80	6.367	12.111
5	137	13.14	4.376	2.091	303.80	6.359	12.089
6	138	13.14	4.376	2.153	303.80	6.360	12.087
7	139	13.15	4.378	2.105	303.80	6.362	12.087
8	140	13.15	4.378	2.159	303.80	6.361	12.072
9	141	13.15	4.378	2.108	303.80	6.359	12.039
10	142	13.15	4.378	2.053	303.80	6.387	12.112
11	143	13.15	4.378	2.070	303.80	6.383	12.108
12	144	13.15	4.378	2.169	303.80	6.382	12.087
13	145	13.15	4.378	2.114	303.80	6.373	12.093
14	146	13.15	4.378	2.137	303.80	6.379	12.094
15	147	13.15	4.378	2.125	303.80	6.375	12.073
16	148	13.15	4.380	2.110	303.80	6.374	12.096
17	149	13.15	4.378	2.175	303.70	6.379	12.083
18	150	13.15	4.380	2.068	303.80	6.399	12.162
19	151	13.15	4.378	2.116	303.80	6.389	12.107
20	152	13.15	4.378	2.122	303.80	6.390	12.089
Mean =			4.378	2.125	303.80	6.370	12.083
Standard Deviation = Stdev =			0.0008	0.0374	0.0224	0.0179	0.0349
Precision Limit = Px = t * Stdev =			0.0016	0.0783	0.0468	0.0374	0.0731
Px / Mean = +/- U (%)			0.037	3.683	0.015	0.588	0.605

N = 20; N-1 = 19; t95(19)=2.093

Table A12. Calculation of precision limit for measured model speed (P_V) and tow force (P_{FD}) and propeller shaft rate (P_N), thrust (P_T) and torque (P_Q), self propulsion test, 17 knot ship speed.

Spot Index i = 1,N	Test Spot Number	Ship Speed (knots)	Model Speed: V (ft/sec)	Model Tow Force: F_D (lbf)	Propeller Shaft Rate: N (RPM)	Propeller Shaft Thrust: T (lbf)	Propeller Shaft Torque: Q (in-lbf)
1	159	17.13	5.706	3.106	394.20	10.364	20.016
2	160	17.13	5.706	3.230	394.20	10.388	20.053
3	161	17.13	5.705	3.194	394.20	10.358	19.985
4	162	17.13	5.705	3.111	394.20	10.387	20.048
5	163	17.13	5.705	3.168	394.20	10.403	20.066
6	164	17.13	5.705	3.152	394.20	10.425	20.118
7	165	17.13	5.705	3.055	394.20	10.440	20.134
8	166	17.12	5.703	3.125	394.20	10.430	20.117
9	167	17.12	5.703	3.053	394.30	10.451	20.152
10	168	17.13	5.705	3.111	394.20	10.448	20.142
11	169	17.13	5.705	3.097	394.20	10.453	20.142
12	170	17.13	5.705	3.055	394.20	10.450	20.117
13	171	17.13	5.705	3.073	394.10	10.455	20.131
14	172	17.12	5.701	3.108	394.20	10.472	20.157
15	173	17.12	5.703	3.158	394.20	10.476	20.147
Mean =			5.704	3.120	394.20	10.427	20.102
Standard Deviation = Stdev =			0.0013	0.0525	0.0378	0.0378	0.0541
Precision Limit = Px = t * Stdev =			0.0028	0.1126	0.0811	0.0812	0.1161
Px / Mean = +/- U (%)			0.049	3.608	0.021	0.778	0.578

N = 15; N-1 = 14; t95(14)=2.145

Table A13. Calculation of precision limit for measured model speed (P_V) and tow force (P_{FD}) and propeller shaft rate (P_N), thrust (P_T) and torque (P_Q), self propulsion test, 20 knot ship speed.

Spot Index i = 1,N	Test Spot Number	Ship Speed (knots)	Model Speed: V (ft/sec)	Model Tow Force: F_D (lbf)	Propeller Shaft Rate: N (RPM)	Propeller Shaft Thrust: T (lbf)	Propeller Shaft Torque: Q (in-lbf)
1	181	20.09	6.692	4.123	469.70	14.738	28.497
2	182	20.09	6.692	4.146	469.60	14.797	28.601
3	183	20.09	6.692	4.112	469.70	14.786	28.570
4	184	20.10	6.694	4.075	469.70	14.838	28.646
5	185	20.10	6.696	4.075	469.70	14.828	28.623
6	186	20.10	6.694	4.074	469.60	14.882	28.702
7	187	20.09	6.692	4.103	469.70	14.913	28.754
8	188	20.09	6.692	4.148	469.70	14.851	28.610
9	189	20.09	6.692	3.988	469.60	14.855	28.628
10	190	20.10	6.694	4.062	469.60	14.860	28.628
11	191	20.10	6.696	4.063	469.60	14.845	28.593
12	192	20.09	6.692	4.054	469.60	14.878	28.651
13	193	20.10	6.694	3.960	469.60	14.819	28.532
Mean =			6.693	4.076	469.65	14.838	28.618
Standard Deviation = Stdev =			0.0013	0.0551	0.0519	0.0456	0.0664
Precision Limit = Px = t * Stdev =			0.0028	0.1200	0.1131	0.0995	0.1448
Px / Mean = +/- U (%)			0.042	2.943	0.024	0.670	0.506

N = 13; N-1 = 12; t95(12)=2.179

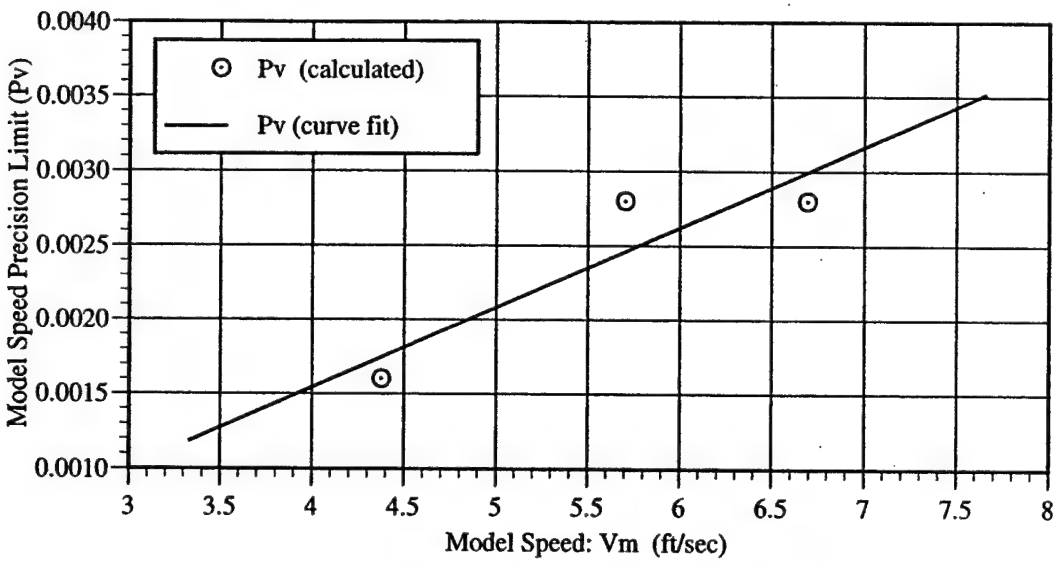

Fig. A3. Model speed precision limit (Pv), self propulsion test.

Table A14. Interpolated values of model speed precision limit (P_V), self propulsion test.

Ship Speed Vs (knots)	Model Speed V (ft/s)	Pv (curve fit) (± ft/s)	Pv (± %)	V + Pv (ft/s)	V - Pv (ft/s)
10.0	3.330	0.0012	0.035	3.332	3.329
11.0	3.664	0.0014	0.037	3.665	3.662
12.0	3.997	0.0015	0.039	3.998	3.995
13.0	4.330	0.0017	0.040	4.331	4.328
14.0	4.663	0.0019	0.041	4.665	4.661
15.0	4.996	0.0021	0.042	4.998	4.994
16.0	5.329	0.0023	0.042	5.331	5.327
17.0	5.662	0.0024	0.043	5.664	5.659
18.0	5.995	0.0026	0.044	5.997	5.992
19.0	6.328	0.0028	0.044	6.331	6.325
20.0	6.661	0.0030	0.045	6.664	6.658
21.0	6.994	0.0032	0.045	6.997	6.991
22.0	7.327	0.0033	0.046	7.330	7.324
23.0	7.660	0.0035	0.046	7.664	7.657

Table A15. Uncertainty analysis of measured model speed (U_V), self propulsion test.

Data Spot No.	Model Speed V (ft/s)	Elemental Bias Errors B_D (ft)	Elemental Bias Errors B_f (1/sec)	Bias Limit B_V (± ft/s)	Precision Limit P_V (± ft/s)	Overall Uncertainty U_V (± ft/s)	Overall Uncertainty U_V (± %)
128	4.019	0.00042	0.0058	0.0010	0.0016	0.0019	0.05
129	4.020	0.00042	0.0058	0.0010	0.0016	0.0019	0.05
130	6.017	0.00042	0.0086	0.0015	0.0026	0.0030	0.05
131	6.017	0.00042	0.0086	0.0015	0.0026	0.0030	0.05
132	6.017	0.00042	0.0086	0.0015	0.0026	0.0030	0.05
133	4.378	0.00042	0.0063	0.0011	0.0017	0.0021	0.05
134	4.378	0.00042	0.0063	0.0011	0.0017	0.0021	0.05
135	4.378	0.00042	0.0063	0.0011	0.0017	0.0021	0.05
136	4.378	0.00042	0.0063	0.0011	0.0017	0.0021	0.05
137	4.376	0.00042	0.0063	0.0011	0.0017	0.0021	0.05
138	4.376	0.00042	0.0063	0.0011	0.0017	0.0021	0.05
139	4.378	0.00042	0.0063	0.0011	0.0017	0.0021	0.05
140	4.378	0.00042	0.0063	0.0011	0.0017	0.0021	0.05
141	4.378	0.00042	0.0063	0.0011	0.0017	0.0021	0.05
142	4.378	0.00042	0.0063	0.0011	0.0017	0.0021	0.05
143	4.378	0.00042	0.0063	0.0011	0.0017	0.0021	0.05
144	4.378	0.00042	0.0063	0.0011	0.0017	0.0021	0.05
145	4.378	0.00042	0.0063	0.0011	0.0017	0.0021	0.05
146	4.378	0.00042	0.0063	0.0011	0.0017	0.0021	0.05
147	4.378	0.00042	0.0063	0.0011	0.0017	0.0021	0.05
148	4.380	0.00042	0.0063	0.0011	0.0017	0.0021	0.05
149	4.378	0.00042	0.0063	0.0011	0.0017	0.0021	0.05
150	4.380	0.00042	0.0063	0.0011	0.0017	0.0021	0.05
151	4.378	0.00042	0.0063	0.0011	0.0017	0.0021	0.05
152	4.378	0.00042	0.0063	0.0011	0.0017	0.0021	0.05
153	3.377	0.00042	0.0049	0.0009	0.0012	0.0015	0.04
154	3.381	0.00042	0.0049	0.0009	0.0012	0.0015	0.04
155	3.384	0.00042	0.0049	0.0009	0.0012	0.0015	0.04
156	5.014	0.00042	0.0072	0.0013	0.0021	0.0024	0.05
157	5.016	0.00042	0.0072	0.0013	0.0021	0.0024	0.05
158	5.016	0.00042	0.0072	0.0013	0.0021	0.0024	0.05
159	5.706	0.00042	0.0082	0.0015	0.0025	0.0029	0.05
160	5.706	0.00042	0.0082	0.0015	0.0025	0.0029	0.05
161	5.705	0.00042	0.0082	0.0014	0.0025	0.0029	0.05
162	5.705	0.00042	0.0082	0.0014	0.0025	0.0029	0.05
163	5.705	0.00042	0.0082	0.0014	0.0025	0.0029	0.05
164	5.705	0.00042	0.0082	0.0014	0.0025	0.0029	0.05
165	5.705	0.00042	0.0082	0.0014	0.0025	0.0029	0.05
166	5.703	0.00042	0.0082	0.0014	0.0025	0.0029	0.05
167	5.703	0.00042	0.0082	0.0014	0.0025	0.0029	0.05
168	5.705	0.00042	0.0082	0.0014	0.0025	0.0029	0.05
169	5.705	0.00042	0.0082	0.0014	0.0025	0.0029	0.05

Table A15. Uncertainty analysis of measured model speed (U_V), self propulsion test, continued.

Data Spot No.	Model Speed V (ft/s)	Elemental Bias Errors B_D (ft)	Elemental Bias Errors B_t (1/sec)	Bias Limit B_V (± ft/s)	Precision Limit P_V (± ft/s)	Overall Uncertainty U_V (± ft/s)	Overall Uncertainty U_V (± %)
170	5.705	0.00042	0.0082	0.0014	0.0025	0.0029	0.05
171	5.705	0.00042	0.0082	0.0014	0.0025	0.0029	0.05
172	5.701	0.00042	0.0082	0.0014	0.0025	0.0029	0.05
173	5.703	0.00042	0.0082	0.0014	0.0025	0.0029	0.05
174	3.691	0.00042	0.0053	0.0009	0.0014	0.0017	0.05
175	3.691	0.00042	0.0053	0.0009	0.0014	0.0017	0.05
176	5.344	0.00042	0.0077	0.0014	0.0023	0.0026	0.05
177	5.344	0.00042	0.0077	0.0014	0.0023	0.0026	0.05
178	5.344	0.00042	0.0077	0.0014	0.0023	0.0026	0.05
179	7.674	0.00042	0.0110	0.0020	0.0035	0.0040	0.05
180	7.679	0.00042	0.0110	0.0020	0.0035	0.0040	0.05
181	**6.692**	**0.00042**	**0.0096**	**0.0017**	**0.0030**	**0.0034**	**0.05**
182	6.692	0.00042	0.0096	0.0017	0.0030	0.0034	0.05
183	6.692	0.00042	0.0096	0.0017	0.0030	0.0034	0.05
184	6.694	0.00042	0.0096	0.0017	0.0030	0.0034	0.05
185	6.696	0.00042	0.0096	0.0017	0.0030	0.0034	0.05
186	6.694	0.00042	0.0096	0.0017	0.0030	0.0034	0.05
187	6.692	0.00042	0.0096	0.0017	0.0030	0.0034	0.05
188	6.692	0.00042	0.0096	0.0017	0.0030	0.0034	0.05
189	6.692	0.00042	0.0096	0.0017	0.0030	0.0034	0.05
190	6.694	0.00042	0.0096	0.0017	0.0030	0.0034	0.05
191	6.696	0.00042	0.0096	0.0017	0.0030	0.0034	0.05
192	6.692	0.00042	0.0096	0.0017	0.0030	0.0034	0.05
193	6.694	0.00042	0.0096	0.0017	0.0030	0.0034	0.05
194	7.013	0.00042	0.0101	0.0018	0.0032	0.0036	0.05
195	7.014	0.00042	0.0101	0.0018	0.0032	0.0036	0.05
196	7.013	0.00042	0.0101	0.0018	0.0032	0.0036	0.05
197	7.344	0.00042	0.0105	0.0019	0.0033	0.0038	0.05
198	7.345	0.00042	0.0105	0.0019	0.0033	0.0038	0.05
199	4.685	0.00042	0.0068	0.0012	0.0019	0.0023	0.05
200	4.687	0.00042	0.0068	0.0012	0.0019	0.0023	0.05
201	4.687	0.00042	0.0068	0.0012	0.0019	0.0023	0.05
202	6.344	0.00042	0.0091	0.0016	0.0028	0.0032	0.05
203	6.344	0.00042	0.0091	0.0016	0.0028	0.0032	0.05
204	6.020	0.00042	0.0086	0.0015	0.0026	0.0030	0.05
205	6.019	0.00042	0.0086	0.0015	0.0026	0.0030	0.05
206	6.020	0.00042	0.0086	0.0015	0.0026	0.0030	0.05
207	6.344	0.00042	0.0091	0.0016	0.0028	0.0032	0.05
208	6.344	0.00042	0.0091	0.0016	0.0028	0.0032	0.05
209	6.346	0.00042	0.0091	0.0016	0.0028	0.0032	0.05

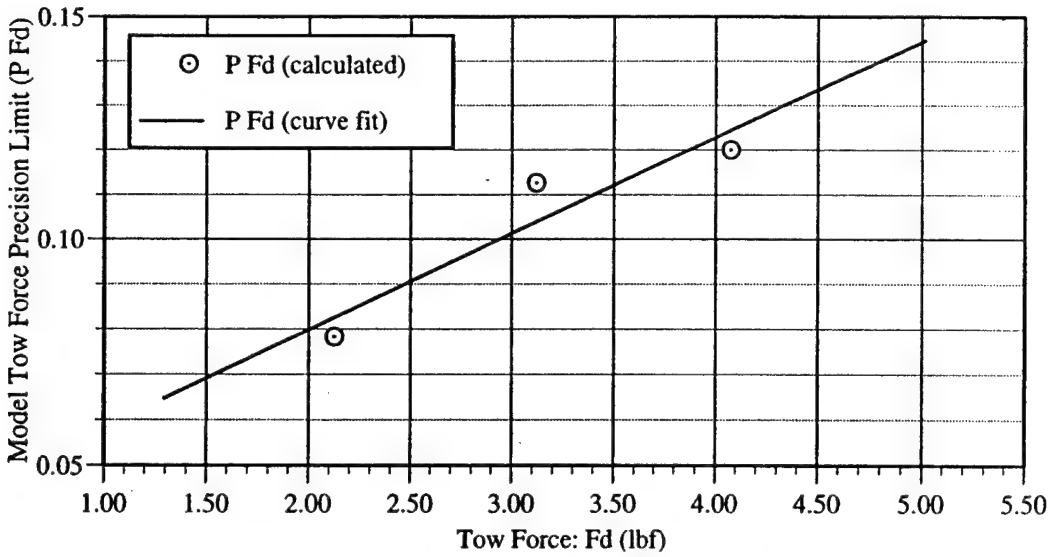

Fig. A4. Model tow force precision limit (P_{FD}), self propulsion test.

Table A16. Interpolated values of model tow force precision limit (P_{FD}), self propulsion test.

Ship Speed Vs (knots)	Model Speed V (ft/s)	Model Tow Force: Fd (lbf)	P_{Fd} (curve fit) (± lbf)	P_{Fd} (± %)	Fd + P_{Fd} (lbf)	Fd - P_{Fd} (lbf)
10.0	3.330	1.292	0.065	5.002	1.357	1.228
11.0	3.664	1.511	0.069	4.589	1.580	1.441
12.0	3.997	1.742	0.074	4.265	1.816	1.668
13.0	4.330	1.986	0.080	4.005	2.065	1.906
14.0	4.663	2.241	0.085	3.793	2.326	2.156
15.0	4.996	2.508	0.091	3.618	2.599	2.417
16.0	5.329	2.786	0.097	3.471	2.883	2.689
17.0	5.662	3.075	0.103	3.347	3.178	2.972
18.0	5.995	3.374	0.109	3.240	3.484	3.265
19.0	6.328	3.684	0.116	3.148	3.800	3.568
20.0	6.661	4.004	0.123	3.068	4.127	3.881
21.0	6.994	4.333	0.130	2.998	4.463	4.203
22.0	7.327	4.672	0.137	2.936	4.809	4.535
23.0	7.660	5.021	0.145	2.882	5.165	4.876

Table A17. Uncertainty analysis of measured model tow force (U_{FD}), self propulsion test.

Data Spot No.	Model Tow Force Fd- (lbf)	Elemental Bias Errors						Bias Limit B Fd (± lbf)	Precision Limit P Fd (± lbf)	Overall Uncertainty U Fd	
		B_{std} (± lbf)	B_{cf} (± lbf)	B_e (± lbf)	B_{data} (± lbf)	$B_{install}$ (± lbf)	$B_{concept}$ (± lbf)			(± lbf)	(± %)
128	1.720	0.0001	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.074	0.075	4.38
129	1.932	0.0001	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.078	0.080	4.13
130	3.282	0.0002	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.107	0.108	3.30
131	3.461	0.0002	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.111	0.112	3.24
132	3.304	0.0002	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.108	0.109	3.30
133	2.143	0.0001	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.083	0.084	3.93
134	2.193	0.0001	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.084	0.085	3.89
135	2.161	0.0001	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.083	0.085	3.92
136	2.133	0.0001	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.083	0.084	3.94
137	2.091	0.0001	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.082	0.083	3.98
138	2.153	0.0001	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.083	0.084	3.92
139	2.105	0.0001	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.082	0.083	3.96
140	2.159	0.0001	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.083	0.085	3.92
141	2.108	0.0001	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.082	0.084	3.96
142	2.053	0.0001	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.081	0.082	4.01
143	2.070	0.0001	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.081	0.083	4.00
144	2.169	0.0001	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.083	0.085	3.91
145	2.114	0.0001	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.082	0.084	3.96
146	2.137	0.0001	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.083	0.084	3.94
147	2.125	0.0001	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.083	0.084	3.95
148	2.110	0.0001	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.082	0.084	3.96
149	2.175	0.0001	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.084	0.085	3.90
150	2.068	0.0001	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.081	0.083	4.00
151	2.116	0.0001	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.082	0.084	3.95
152	2.122	0.0001	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.082	0.084	3.95
153	1.297	0.0001	0.0055	0.0007	0.0140	0.0000	0.0000	0.015	0.065	0.066	5.12
154	1.329	0.0001	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.065	0.067	5.05
155	1.267	0.0001	0.0055	0.0007	0.0140	0.0000	0.0000	0.015	0.064	0.066	5.20
156	2.413	0.0002	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.089	0.090	3.73
157	2.450	0.0002	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.089	0.091	3.70
158	2.393	0.0002	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.088	0.090	3.74
159	3.106	0.0002	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.104	0.105	3.37
160	3.230	0.0002	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.106	0.107	3.32
161	3.194	0.0002	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.105	0.107	3.34
162	3.111	0.0002	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.104	0.105	3.37
163	3.168	0.0002	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.105	0.106	3.35
164	3.152	0.0002	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.105	0.106	3.35
165	3.055	0.0002	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.102	0.104	3.39
166	3.125	0.0002	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.104	0.105	3.36
167	3.053	0.0002	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.102	0.104	3.39
168	3.111	0.0002	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.104	0.105	3.37
169	3.097	0.0002	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.103	0.104	3.37

Table A17. Uncertainty analysis of measured model tow force (U_{FD}), self propulsion test, continued.

Data Spot No.	Model Tow Force Fd (lbf)	Elemental Bias Errors						Bias Limit B Fd (± lbf)	Precision Limit P Fd (± lbf)	Overall Uncertainty U Fd	
		B_{std} (± lbf)	B_{cf} (± lbf)	B_e (± lbf)	B_{data} (± lbf)	$B_{install}$ (± lbf)	$B_{concept}$ (± lbf)			(± lbf)	(± %)
170	3.055	0.0002	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.102	0.104	3.39
171	3.073	0.0002	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.103	0.104	3.38
172	3.108	0.0002	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.104	0.105	3.37
173	3.158	0.0002	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.105	0.106	3.35
174	1.673	0.0001	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.073	0.074	4.44
175	1.729	0.0001	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.074	0.076	4.37
176	2.737	0.0002	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.096	0.097	3.54
177	2.693	0.0002	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.095	0.096	3.56
178	2.695	0.0002	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.095	0.096	3.56
179	4.461	0.0002	0.0055	0.0007	0.0140	0.0002	0.0000	0.015	0.133	0.134	2.99
180	4.664	0.0002	0.0055	0.0007	0.0140	0.0002	0.0000	0.015	0.137	0.138	2.96
181	**4.123**	**0.0002**	**0.0055**	**0.0007**	**0.0140**	**0.0002**	**0.0000**	**0.015**	**0.125**	**0.126**	**3.06**
182	4.146	0.0002	0.0055	0.0007	0.0140	0.0002	0.0000	0.015	0.126	0.127	3.06
183	4.112	0.0002	0.0055	0.0007	0.0140	0.0002	0.0000	0.015	0.125	0.126	3.07
184	4.075	0.0002	0.0055	0.0007	0.0140	0.0002	0.0000	0.015	0.124	0.125	3.07
185	4.075	0.0002	0.0055	0.0007	0.0140	0.0002	0.0000	0.015	0.124	0.125	3.07
186	4.074	0.0002	0.0055	0.0007	0.0140	0.0002	0.0000	0.015	0.124	0.125	3.07
187	4.103	0.0002	0.0055	0.0007	0.0140	0.0002	0.0000	0.015	0.125	0.126	3.07
188	4.148	0.0002	0.0055	0.0007	0.0140	0.0002	0.0000	0.015	0.126	0.127	3.06
189	3.988	0.0002	0.0055	0.0007	0.0140	0.0002	0.0000	0.015	0.123	0.123	3.10
190	4.062	0.0002	0.0055	0.0007	0.0140	0.0002	0.0000	0.015	0.124	0.125	3.08
191	4.063	0.0002	0.0055	0.0007	0.0140	0.0002	0.0000	0.015	0.124	0.125	3.08
192	4.054	0.0002	0.0055	0.0007	0.0140	0.0002	0.0000	0.015	0.124	0.125	3.08
193	3.960	0.0002	0.0055	0.0007	0.0140	0.0002	0.0000	0.015	0.122	0.123	3.10
194	4.066	0.0002	0.0055	0.0007	0.0140	0.0002	0.0000	0.015	0.124	0.125	3.08
195	4.076	0.0002	0.0055	0.0007	0.0140	0.0002	0.0000	0.015	0.124	0.125	3.07
196	4.129	0.0002	0.0055	0.0007	0.0140	0.0002	0.0000	0.015	0.126	0.126	3.06
197	4.142	0.0002	0.0055	0.0007	0.0140	0.0002	0.0000	0.015	0.126	0.127	3.06
198	4.426	0.0002	0.0055	0.0007	0.0140	0.0002	0.0000	0.015	0.132	0.133	3.00
199	2.320	0.0001	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.087	0.088	3.79
200	2.413	0.0002	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.089	0.090	3.73
201	2.259	0.0001	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.085	0.087	3.84
202	3.202	0.0002	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.106	0.107	3.33
203	3.219	0.0002	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.106	0.107	3.33
204	3.438	0.0002	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.111	0.112	3.25
205	3.473	0.0002	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.111	0.112	3.24
206	3.481	0.0002	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.112	0.113	3.24
207	3.726	0.0002	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.117	0.118	3.16
208	3.761	0.0002	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.118	0.119	3.15
209	3.587	0.0002	0.0055	0.0007	0.0140	0.0001	0.0000	0.015	0.114	0.115	3.20

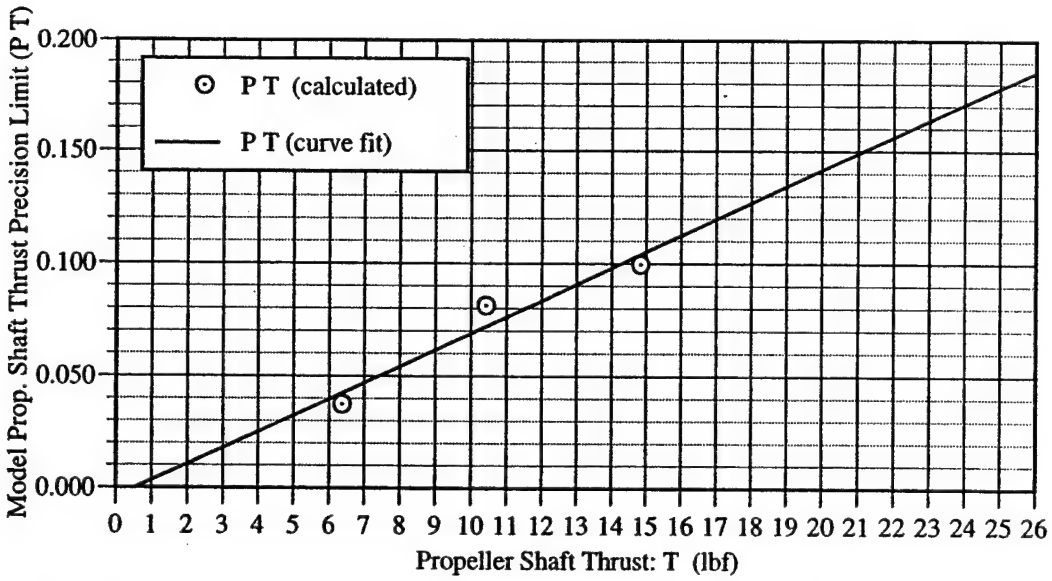

Fig. A5. Model propeller shaft thrust precision limit (P_T), self propulsion test.

Table A18. Interpolated values of model propeller shaft thrust precision limit (P_T), self propulsion test.

Ship Speed Vs (knots)	Model Speed V (ft/s)	Model Propeller Shaft Thrust, T (lbf)	P_T (curve fit) (± lbf)	P_T (± %)	$T + P_T$ (lbf)	$T - P_T$ (lbf)
10.0	3.330	3.680	0.023	0.616	3.703	3.657
11.0	3.664	4.460	0.028	0.636	4.488	4.432
12.0	3.997	5.320	0.035	0.651	5.355	5.285
13.0	4.330	6.220	0.041	0.662	6.261	6.179
14.0	4.663	7.150	0.048	0.671	7.198	7.102
15.0	4.996	8.070	0.055	0.677	8.125	8.015
16.0	5.329	9.030	0.062	0.683	9.092	8.968
17.0	5.662	10.160	0.070	0.688	10.230	10.090
18.0	5.995	11.450	0.079	0.693	11.529	11.371
19.0	6.328	13.020	0.091	0.697	13.111	12.929
20.0	6.661	14.730	0.103	0.701	14.833	14.627
21.0	6.994	16.700	0.118	0.704	16.818	16.582
22.0	7.327	19.400	0.137	0.707	19.537	19.263
23.0	7.660	24.880	0.177	0.712	25.057	24.703

Table A19. Uncertainty analysis of measured model propeller shaft thrust (U_T), self propulsion test.

Data Spot No.	Model Prop. Shaft Thrust T (lbf)	Elemental Bias Errors						Bias Limit	Precision Limit	Overall Uncertainty	
		B_{std} (± lbf)	B_{cf} (± lbf)	B_e (± lbf)	B_{data} (± lbf)	$B_{install}$ (± lbf)	$B_{concept}$ (± lbf)	B_T (± lbf)	P_T (± lbf)	U_T (± lbf)	U_T (± %)
128	5.491	0.0115	0.0344	0.0012	0.0114	0.0410	0.0000	0.056	0.036	0.066	1.21
129	5.488	0.0115	0.0344	0.0012	0.0114	0.0410	0.0000	0.056	0.036	0.066	1.21
130	11.755	0.0247	0.0344	0.0012	0.0114	0.0410	0.0000	0.060	0.082	0.101	0.86
131	11.754	0.0247	0.0344	0.0012	0.0114	0.0410	0.0000	0.060	0.082	0.101	0.86
132	11.767	0.0247	0.0344	0.0012	0.0114	0.0410	0.0000	0.060	0.082	0.101	0.86
133	6.335	0.0133	0.0344	0.0012	0.0114	0.0410	0.0000	0.056	0.042	0.070	1.11
134	6.333	0.0133	0.0344	0.0012	0.0114	0.0410	0.0000	0.056	0.042	0.070	1.11
135	6.346	0.0133	0.0344	0.0012	0.0114	0.0410	0.0000	0.056	0.042	0.070	1.11
136	6.367	0.0134	0.0344	0.0012	0.0114	0.0410	0.0000	0.056	0.042	0.070	1.11
137	6.359	0.0134	0.0344	0.0012	0.0114	0.0410	0.0000	0.056	0.042	0.070	1.11
138	6.360	0.0134	0.0344	0.0012	0.0114	0.0410	0.0000	0.056	0.042	0.070	1.11
139	6.362	0.0134	0.0344	0.0012	0.0114	0.0410	0.0000	0.056	0.042	0.070	1.11
140	6.361	0.0134	0.0344	0.0012	0.0114	0.0410	0.0000	0.056	0.042	0.070	1.11
141	6.359	0.0134	0.0344	0.0012	0.0114	0.0410	0.0000	0.056	0.042	0.070	1.11
142	6.387	0.0134	0.0344	0.0012	0.0114	0.0410	0.0000	0.056	0.042	0.071	1.10
143	6.383	0.0134	0.0344	0.0012	0.0114	0.0410	0.0000	0.056	0.042	0.071	1.10
144	6.382	0.0134	0.0344	0.0012	0.0114	0.0410	0.0000	0.056	0.042	0.070	1.10
145	6.373	0.0134	0.0344	0.0012	0.0114	0.0410	0.0000	0.056	0.042	0.070	1.11
146	6.379	0.0134	0.0344	0.0012	0.0114	0.0410	0.0000	0.056	0.042	0.070	1.10
147	6.375	0.0134	0.0344	0.0012	0.0114	0.0410	0.0000	0.056	0.042	0.070	1.11
148	6.374	0.0134	0.0344	0.0012	0.0114	0.0410	0.0000	0.056	0.042	0.070	1.11
149	6.379	0.0134	0.0344	0.0012	0.0114	0.0410	0.0000	0.056	0.042	0.070	1.10
150	6.399	0.0134	0.0344	0.0012	0.0114	0.0410	0.0000	0.056	0.042	0.071	1.10
151	6.389	0.0134	0.0344	0.0012	0.0114	0.0410	0.0000	0.056	0.042	0.071	1.10
152	6.390	0.0134	0.0344	0.0012	0.0114	0.0410	0.0000	0.056	0.042	0.071	1.10
153	3.764	0.0079	0.0344	0.0012	0.0114	0.0410	0.0000	0.055	0.023	0.060	1.59
154	3.738	0.0079	0.0344	0.0012	0.0114	0.0410	0.0000	0.055	0.023	0.060	1.60
155	3.704	0.0078	0.0344	0.0012	0.0114	0.0410	0.0000	0.055	0.023	0.060	1.61
156	8.122	0.0171	0.0344	0.0012	0.0114	0.0410	0.0000	0.057	0.055	0.079	0.98
157	8.143	0.0171	0.0344	0.0012	0.0114	0.0410	0.0000	0.057	0.055	0.080	0.98
158	8.145	0.0171	0.0344	0.0012	0.0114	0.0410	0.0000	0.057	0.055	0.080	0.98
159	10.364	0.0218	0.0344	0.0012	0.0114	0.0410	0.0000	0.059	0.071	0.093	0.89
160	10.388	0.0218	0.0344	0.0012	0.0114	0.0410	0.0000	0.059	0.072	0.093	0.89
161	10.358	0.0218	0.0344	0.0012	0.0114	0.0410	0.0000	0.059	0.071	0.093	0.89
162	10.387	0.0218	0.0344	0.0012	0.0114	0.0410	0.0000	0.059	0.072	0.093	0.89
163	10.403	0.0219	0.0344	0.0012	0.0114	0.0410	0.0000	0.059	0.072	0.093	0.89
164	10.425	0.0219	0.0344	0.0012	0.0114	0.0410	0.0000	0.059	0.072	0.093	0.89
165	10.440	0.0219	0.0344	0.0012	0.0114	0.0410	0.0000	0.059	0.072	0.093	0.89
166	10.430	0.0219	0.0344	0.0012	0.0114	0.0410	0.0000	0.059	0.072	0.093	0.89
167	10.451	0.0220	0.0344	0.0012	0.0114	0.0410	0.0000	0.059	0.072	0.093	0.89
168	10.448	0.0219	0.0344	0.0012	0.0114	0.0410	0.0000	0.059	0.072	0.093	0.89
169	10.453	0.0220	0.0344	0.0012	0.0114	0.0410	0.0000	0.059	0.072	0.093	0.89

Table A19. Uncertainty analysis of measured model propeller shaft thrust (U_T), self propulsion test, continued.

Data Spot No.	Model Prop. Shaft Thrust T (lbf)	Elemental Bias Errors						Bias Limit B_T	Precision Limit P_T	Overall Uncertainty U_T	
		B_{std} (± lbf)	B_{cf} (± lbf)	B_e (± lbf)	B_{data} (± lbf)	$B_{install}$ (± lbf)	$B_{concept}$ (± lbf)	(± lbf)	(± lbf)	(± lbf)	(± %)
170	10.450	0.0220	0.0344	0.0012	0.0114	0.0410	0.0000	0.059	0.072	0.093	0.89
171	10.455	0.0220	0.0344	0.0012	0.0114	0.0410	0.0000	0.059	0.072	0.093	0.89
172	10.472	0.0220	0.0344	0.0012	0.0114	0.0410	0.0000	0.059	0.072	0.093	0.89
173	10.476	0.0220	0.0344	0.0012	0.0114	0.0410	0.0000	0.059	0.072	0.093	0.89
174	4.358	0.0092	0.0344	0.0012	0.0114	0.0410	0.0000	0.055	0.028	0.062	1.42
175	4.352	0.0091	0.0344	0.0012	0.0114	0.0410	0.0000	0.055	0.028	0.062	1.42
176	9.147	0.0192	0.0344	0.0012	0.0114	0.0410	0.0000	0.058	0.063	0.085	0.93
177	9.177	0.0193	0.0344	0.0012	0.0114	0.0410	0.0000	0.058	0.063	0.085	0.93
178	9.213	0.0194	0.0344	0.0012	0.0114	0.0410	0.0000	0.058	0.063	0.086	0.93
179	25.788	0.0542	0.0344	0.0012	0.0114	0.0410	0.0000	0.077	0.184	0.199	0.77
180	25.724	0.0540	0.0344	0.0012	0.0114	0.0410	0.0000	0.077	0.183	0.199	0.77
181	**14.738**	**0.0310**	**0.0344**	**0.0012**	**0.0114**	**0.0410**	**0.0000**	**0.063**	**0.103**	**0.121**	**0.82**
182	14.797	0.0311	0.0344	0.0012	0.0114	0.0410	0.0000	0.063	0.104	0.121	0.82
183	14.786	0.0311	0.0344	0.0012	0.0114	0.0410	0.0000	0.063	0.104	0.121	0.82
184	14.838	0.0312	0.0344	0.0012	0.0114	0.0410	0.0000	0.063	0.104	0.122	0.82
185	14.828	0.0311	0.0344	0.0012	0.0114	0.0410	0.0000	0.063	0.104	0.122	0.82
186	14.882	0.0313	0.0344	0.0012	0.0114	0.0410	0.0000	0.063	0.104	0.122	0.82
187	14.913	0.0313	0.0344	0.0012	0.0114	0.0410	0.0000	0.063	0.105	0.122	0.82
188	14.851	0.0312	0.0344	0.0012	0.0114	0.0410	0.0000	0.063	0.104	0.122	0.82
189	14.855	0.0312	0.0344	0.0012	0.0114	0.0410	0.0000	0.063	0.104	0.122	0.82
190	14.860	0.0312	0.0344	0.0012	0.0114	0.0410	0.0000	0.063	0.104	0.122	0.82
191	14.845	0.0312	0.0344	0.0012	0.0114	0.0410	0.0000	0.063	0.104	0.122	0.82
192	14.878	0.0313	0.0344	0.0012	0.0114	0.0410	0.0000	0.063	0.104	0.122	0.82
193	14.819	0.0311	0.0344	0.0012	0.0114	0.0410	0.0000	0.063	0.104	0.121	0.82
194	16.584	0.0348	0.0344	0.0012	0.0114	0.0410	0.0000	0.065	0.117	0.134	0.81
195	16.607	0.0349	0.0344	0.0012	0.0114	0.0410	0.0000	0.065	0.117	0.134	0.81
196	16.634	0.0349	0.0344	0.0012	0.0114	0.0410	0.0000	0.065	0.117	0.134	0.80
197	20.153	0.0423	0.0344	0.0012	0.0114	0.0410	0.0000	0.069	0.143	0.159	0.79
198	19.999	0.0420	0.0344	0.0012	0.0114	0.0410	0.0000	0.069	0.142	0.158	0.79
199	7.132	0.0150	0.0344	0.0012	0.0114	0.0410	0.0000	0.057	0.048	0.074	1.04
200	7.111	0.0149	0.0344	0.0012	0.0114	0.0410	0.0000	0.057	0.048	0.074	1.04
201	7.111	0.0149	0.0344	0.0012	0.0114	0.0410	0.0000	0.057	0.048	0.074	1.04
202	13.643	0.0287	0.0344	0.0012	0.0114	0.0410	0.0000	0.062	0.095	0.114	0.83
203	13.636	0.0286	0.0344	0.0012	0.0114	0.0410	0.0000	0.062	0.095	0.114	0.83
204	11.441	0.0240	0.0344	0.0012	0.0114	0.0410	0.0000	0.060	0.079	0.099	0.87
205	11.459	0.0241	0.0344	0.0012	0.0114	0.0410	0.0000	0.060	0.079	0.099	0.87
206	11.449	0.0241	0.0344	0.0012	0.0114	0.0410	0.0000	0.060	0.079	0.099	0.87
207	12.835	0.0270	0.0344	0.0012	0.0114	0.0410	0.0000	0.061	0.089	0.108	0.84
208	12.897	0.0271	0.0344	0.0012	0.0114	0.0410	0.0000	0.061	0.090	0.109	0.84
209	12.967	0.0272	0.0344	0.0012	0.0114	0.0410	0.0000	0.061	0.090	0.109	0.84

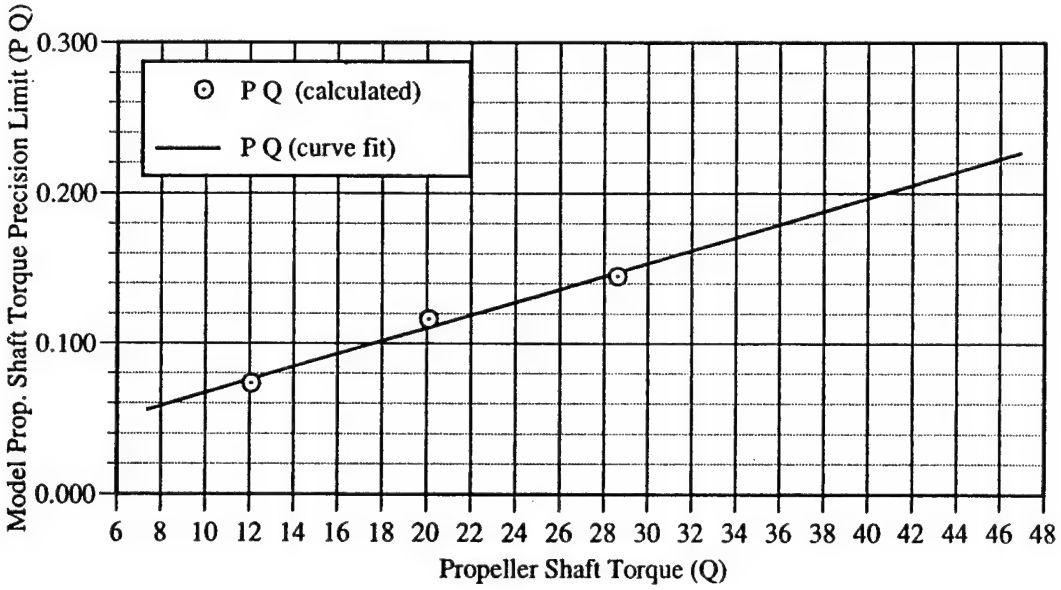

Fig. A6. Model propeller shaft torque precision limit (PQ), self propulsion test.

Table A20. Interpolated values of model propeller shaft torque precision limit (P_Q), self propulsion test.

Ship Speed Vs (knots)	Model Speed V (ft/s)	Model Propeller Shaft Torque, Q (in-lbf)	P_Q (curve fit) (± in-lbf)	P_Q (± %)	$Q + P_Q$ (in-lbf)	$Q - P_Q$ (in-lbf)
10.0	3.330	7.360	0.055	0.754	7.415	7.305
11.0	3.664	8.920	0.062	0.698	8.982	8.858
12.0	3.997	10.630	0.070	0.655	10.700	10.560
13.0	4.330	12.390	0.077	0.624	12.467	12.313
14.0	4.663	14.040	0.084	0.601	14.124	13.956
15.0	4.996	15.810	0.092	0.582	15.902	15.718
16.0	5.329	17.780	0.101	0.566	17.881	17.679
17.0	5.662	19.990	0.110	0.551	20.100	19.880
18.0	5.995	22.560	0.121	0.537	22.681	22.439
19.0	6.328	25.330	0.133	0.526	25.463	25.197
20.0	6.661	28.550	0.147	0.515	28.697	28.403
21.0	6.994	32.560	0.165	0.505	32.725	32.395
22.0	7.327	37.650	0.187	0.495	37.837	37.463
23.0	7.660	46.960	0.227	0.483	47.187	46.733

Table A21. Uncertainty analysis of measured model propeller shaft torque (U_Q), self propulsion test.

Data Spot No.	Model Prop. Shaft Torque Q (in-lbf)	Elemental Bias Errors						Bias Limit B_Q	Precision Limit P_Q	Overall Uncertainty U_Q	
		B_{std} (± in-lbf)	B_{cf} (±in-lbf)	B_e (±in-lbf)	B_{data} (±in-lbf)	$B_{install}$ (±in-lbf)	$B_{concept}$ (± in-lbf)	(± in-lbf)	(± in-lbf)	(± in-lbf)	(± %)
128	10.642	0.0054	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.070	0.122	1.14
129	10.624	0.0054	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.070	0.122	1.15
130	22.835	0.0115	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.122	0.158	0.69
131	22.812	0.0115	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.122	0.158	0.69
132	22.831	0.0115	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.122	0.158	0.69
133	12.016	0.0061	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.076	0.125	1.04
134	12.013	0.0061	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.076	0.125	1.04
135	12.038	0.0061	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.076	0.125	1.04
136	12.111	0.0061	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.076	0.126	1.04
137	12.089	0.0061	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.076	0.126	1.04
138	12.087	0.0061	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.076	0.126	1.04
139	12.087	0.0061	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.076	0.126	1.04
140	12.072	0.0061	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.076	0.126	1.04
141	12.039	0.0061	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.076	0.125	1.04
142	12.112	0.0061	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.076	0.126	1.04
143	12.108	0.0061	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.076	0.126	1.04
144	12.087	0.0061	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.076	0.126	1.04
145	12.093	0.0061	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.076	0.126	1.04
146	12.094	0.0061	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.076	0.126	1.04
147	12.073	0.0061	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.076	0.126	1.04
148	12.096	0.0061	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.076	0.126	1.04
149	12.083	0.0061	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.076	0.126	1.04
150	12.162	0.0061	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.076	0.126	1.03
151	12.107	0.0061	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.076	0.126	1.04
152	12.089	0.0061	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.076	0.126	1.04
153	7.464	0.0038	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.056	0.114	1.53
154	7.383	0.0038	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.056	0.114	1.55
155	7.330	0.0037	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.055	0.114	1.56
156	16.010	0.0081	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.093	0.137	0.85
157	16.033	0.0081	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.093	0.137	0.85
158	16.014	0.0081	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.093	0.137	0.85
159	20.016	0.0101	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.110	0.149	0.74
160	20.053	0.0101	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.110	0.149	0.74
161	19.985	0.0101	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.110	0.149	0.75
162	20.048	0.0101	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.110	0.149	0.74
163	20.066	0.0101	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.110	0.149	0.74
164	20.118	0.0101	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.111	0.149	0.74
165	20.134	0.0101	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.111	0.149	0.74
166	20.117	0.0101	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.111	0.149	0.74
167	20.152	0.0102	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.111	0.149	0.74
168	20.142	0.0101	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.111	0.149	0.74
169	20.142	0.0101	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.111	0.149	0.74

Table A21. Uncertainty analysis of measured model propeller shaft torque (U_Q), self propulsion test, continued.

Data Spot No.	Model Prop. Shaft Torque Q (in-lbf)	Elemental Bias Errors						Bias Limit B_Q (± in-lbf)	Precision Limit P_Q (± in-lbf)	Overall Uncertainty U_Q	
		B_{std} (± in-lbf)	B_{cf} (±in-lbf)	B_e (±in-lbf)	B_{data} (±in-lbf)	$B_{install}$ (±in-lbf)	$B_{concept}$ (± in-lbf)			(± in-lbf)	(± %)
170	20.117	0.0101	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.111	0.149	0.74
171	20.131	0.0101	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.111	0.149	0.74
172	20.157	0.0102	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.111	0.149	0.74
173	20.147	0.0101	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.111	0.149	0.74
174	8.717	0.0044	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.061	0.117	1.34
175	8.711	0.0044	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.061	0.117	1.35
176	18.039	0.0091	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.102	0.143	0.79
177	18.067	0.0091	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.102	0.143	0.79
178	18.112	0.0091	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.102	0.143	0.79
179	48.645	0.0244	0.0834	0.0019	0.0199	0.0510	0.0000	0.103	0.234	0.256	0.53
180	48.551	0.0244	0.0834	0.0019	0.0199	0.0510	0.0000	0.103	0.234	0.255	0.53
181	**28.497**	**0.0143**	**0.0834**	**0.0019**	**0.0199**	**0.0510**	**0.0000**	**0.101**	**0.147**	**0.178**	**0.62**
182	28.601	0.0144	0.0834	0.0019	0.0199	0.0510	0.0000	0.101	0.147	0.179	0.62
183	28.570	0.0144	0.0834	0.0019	0.0199	0.0510	0.0000	0.101	0.147	0.178	0.62
184	28.646	0.0144	0.0834	0.0019	0.0199	0.0510	0.0000	0.101	0.148	0.179	0.62
185	28.623	0.0144	0.0834	0.0019	0.0199	0.0510	0.0000	0.101	0.147	0.179	0.62
186	28.702	0.0144	0.0834	0.0019	0.0199	0.0510	0.0000	0.101	0.148	0.179	0.62
187	28.754	0.0145	0.0834	0.0019	0.0199	0.0510	0.0000	0.101	0.148	0.179	0.62
188	28.610	0.0144	0.0834	0.0019	0.0199	0.0510	0.0000	0.101	0.147	0.179	0.62
189	28.628	0.0144	0.0834	0.0019	0.0199	0.0510	0.0000	0.101	0.148	0.179	0.62
190	28.628	0.0144	0.0834	0.0019	0.0199	0.0510	0.0000	0.101	0.148	0.179	0.62
191	28.593	0.0144	0.0834	0.0019	0.0199	0.0510	0.0000	0.101	0.147	0.179	0.62
192	28.651	0.0144	0.0834	0.0019	0.0199	0.0510	0.0000	0.101	0.148	0.179	0.62
193	28.532	0.0144	0.0834	0.0019	0.0199	0.0510	0.0000	0.101	0.147	0.178	0.62
194	32.383	0.0163	0.0834	0.0019	0.0199	0.0510	0.0000	0.101	0.164	0.192	0.59
195	32.422	0.0163	0.0834	0.0019	0.0199	0.0510	0.0000	0.101	0.164	0.193	0.59
196	32.422	0.0163	0.0834	0.0019	0.0199	0.0510	0.0000	0.101	0.164	0.193	0.59
197	38.824	0.0195	0.0834	0.0019	0.0199	0.0510	0.0000	0.102	0.192	0.217	0.56
198	38.574	0.0194	0.0834	0.0019	0.0199	0.0510	0.0000	0.102	0.191	0.216	0.56
199	14.101	0.0071	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.085	0.131	0.93
200	14.042	0.0071	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.084	0.131	0.93
201	14.058	0.0071	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.084	0.131	0.93
202	26.557	0.0134	0.0834	0.0019	0.0199	0.0510	0.0000	0.101	0.139	0.171	0.64
203	26.554	0.0134	0.0834	0.0019	0.0199	0.0510	0.0000	0.101	0.139	0.171	0.64
204	22.524	0.0113	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.121	0.157	0.70
205	22.537	0.0113	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.121	0.157	0.70
206	22.521	0.0113	0.0834	0.0019	0.0199	0.0510	0.0000	0.100	0.121	0.157	0.70
207	25.284	0.0127	0.0834	0.0019	0.0199	0.0510	0.0000	0.101	0.133	0.167	0.66
208	25.355	0.0128	0.0834	0.0019	0.0199	0.0510	0.0000	0.101	0.133	0.167	0.66
209	25.480	0.0128	0.0834	0.0019	0.0199	0.0510	0.0000	0.101	0.134	0.167	0.66

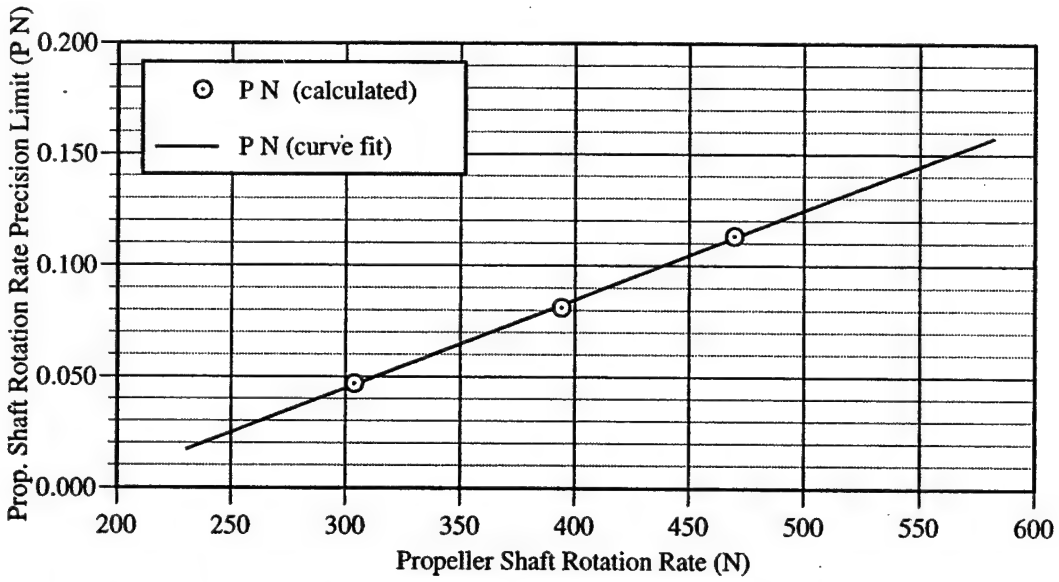

Fig. A7. Model propeller shaft rotation rate precision limit (P_N), self propulsion test.

Table A22. Interpolated values of model propeller shaft rotation rate precision limit (P_N), self propulsion test.

Ship Speed Vs (knots)	Model Speed V (ft/s)	Model Propeller Shaft Rate, N (RPM)	P_N (curve fit) (RPM)	P_N (± %)	N + P_N (RPM)	N - P_N (RPM)
10.0	3.330	230.56	0.0170	0.007	230.58	230.54
11.0	3.664	255.78	0.0271	0.011	255.81	255.75
12.0	3.997	280.10	0.0368	0.013	280.14	280.06
13.0	4.330	301.71	0.0454	0.015	301.76	301.66
14.0	4.663	323.39	0.0541	0.017	323.44	323.34
15.0	4.996	345.83	0.0630	0.018	345.89	345.77
16.0	5.329	367.85	0.0718	0.020	367.92	367.78
17.0	5.662	390.47	0.0808	0.021	390.55	390.39
18.0	5.995	413.83	0.0902	0.022	413.92	413.74
19.0	6.328	438.88	0.1002	0.023	438.98	438.78
20.0	6.661	465.50	0.1108	0.024	465.61	465.39
21.0	6.994	493.48	0.1219	0.025	493.60	493.36
22.0	7.327	528.67	0.1360	0.026	528.81	528.53
23.0	7.660	582.48	0.1575	0.027	582.64	582.32

Table A23. Uncertainty analysis of measured model propeller shaft rotation rate (U_N), self propulsion test.

Data Spot No.	Propeller Shaft Rotation Rate N (RPM)	Elemental Bias Error B_f (1/sec)	Bias Limit B_N (± RPM)	Precision Limit P_N (± RPM)	Overall Uncertainty U_N (± RPM)	(± %)
128	281.3	0.0041	0.004	0.037	0.04	0.01
129	281.3	0.0041	0.004	0.037	0.04	0.01
130	417.5	0.0060	0.006	0.092	0.09	0.02
131	417.5	0.0060	0.006	0.092	0.09	0.02
132	417.5	0.0060	0.006	0.092	0.09	0.02
133	303.8	0.0044	0.004	0.046	0.05	0.02
134	303.8	0.0044	0.004	0.046	0.05	0.02
135	303.8	0.0044	0.004	0.046	0.05	0.02
136	303.8	0.0044	0.004	0.046	0.05	0.02
137	303.8	0.0044	0.004	0.046	0.05	0.02
138	303.8	0.0044	0.004	0.046	0.05	0.02
139	303.8	0.0044	0.004	0.046	0.05	0.02
140	303.8	0.0044	0.004	0.046	0.05	0.02
141	303.8	0.0044	0.004	0.046	0.05	0.02
142	303.8	0.0044	0.004	0.046	0.05	0.02
143	303.8	0.0044	0.004	0.046	0.05	0.02
144	303.8	0.0044	0.004	0.046	0.05	0.02
145	303.8	0.0044	0.004	0.046	0.05	0.02
146	303.8	0.0044	0.004	0.046	0.05	0.02
147	303.8	0.0044	0.004	0.046	0.05	0.02
148	303.8	0.0044	0.004	0.046	0.05	0.02
149	303.7	0.0044	0.004	0.046	0.05	0.02
150	303.8	0.0044	0.004	0.046	0.05	0.02
151	303.8	0.0044	0.004	0.046	0.05	0.02
152	303.8	0.0044	0.004	0.046	0.05	0.02
153	234.9	0.0034	0.003	0.019	0.02	0.01
154	234.5	0.0034	0.003	0.019	0.02	0.01
155	234.1	0.0034	0.003	0.018	0.02	0.01
156	348.3	0.0050	0.005	0.064	0.06	0.02
157	348.3	0.0050	0.005	0.064	0.06	0.02
158	348.3	0.0050	0.005	0.064	0.06	0.02
159	394.2	0.0057	0.006	0.082	0.08	0.02
160	394.2	0.0057	0.006	0.082	0.08	0.02
161	394.2	0.0057	0.006	0.082	0.08	0.02
162	394.2	0.0057	0.006	0.082	0.08	0.02
163	394.2	0.0057	0.006	0.082	0.08	0.02
164	394.2	0.0057	0.006	0.082	0.08	0.02
165	394.2	0.0057	0.006	0.082	0.08	0.02
166	394.2	0.0057	0.006	0.082	0.08	0.02
167	394.3	0.0057	0.006	0.082	0.08	0.02
168	394.2	0.0057	0.006	0.082	0.08	0.02
169	394.2	0.0057	0.006	0.082	0.08	0.02

Table A23. Uncertainty analysis of measured model propeller shaft rotation rate (U_N), self propulsion test, continued.

Data Spot No.	Propeller Shaft Rotation Rate N (RPM)	Elemental Bias Error B_f (1/sec)	Bias Limit B_N (± RPM)	Precision Limit P_N (± RPM)	Overall Uncertainty U_N (± RPM)	(± %)
170	394.2	0.0057	0.006	0.082	0.08	0.02
171	394.1	0.0057	0.006	0.082	0.08	0.02
172	394.2	0.0057	0.006	0.082	0.08	0.02
173	394.2	0.0057	0.006	0.082	0.08	0.02
174	255.4	0.0037	0.004	0.027	0.03	0.01
175	255.4	0.0037	0.004	0.027	0.03	0.01
176	370.4	0.0054	0.005	0.073	0.07	0.02
177	370.4	0.0054	0.005	0.073	0.07	0.02
178	370.4	0.0054	0.005	0.073	0.07	0.02
179	588.4	0.0085	0.008	0.160	0.16	0.03
180	588.4	0.0085	0.008	0.160	0.16	0.03
181	**469.7**	**0.0068**	**0.007**	**0.112**	**0.11**	**0.02**
182	469.6	0.0068	0.007	0.112	0.11	0.02
183	469.7	0.0068	0.007	0.112	0.11	0.02
184	469.7	0.0068	0.007	0.112	0.11	0.02
185	469.7	0.0068	0.007	0.112	0.11	0.02
186	469.6	0.0068	0.007	0.112	0.11	0.02
187	469.7	0.0068	0.007	0.112	0.11	0.02
188	469.7	0.0068	0.007	0.112	0.11	0.02
189	469.6	0.0068	0.007	0.112	0.11	0.02
190	469.6	0.0068	0.007	0.112	0.11	0.02
191	469.6	0.0068	0.007	0.112	0.11	0.02
192	469.6	0.0068	0.007	0.112	0.11	0.02
193	469.6	0.0068	0.007	0.112	0.11	0.02
194	496.5	0.0072	0.007	0.123	0.12	0.02
195	496.4	0.0071	0.007	0.123	0.12	0.02
196	496.4	0.0071	0.007	0.123	0.12	0.02
197	536.1	0.0077	0.008	0.139	0.14	0.03
198	535.2	0.0077	0.008	0.139	0.14	0.03
199	326.0	0.0047	0.005	0.055	0.06	0.02
200	326.0	0.0047	0.005	0.055	0.06	0.02
201	326.0	0.0047	0.005	0.055	0.06	0.02
202	448.1	0.0065	0.006	0.104	0.10	0.02
203	448.1	0.0065	0.006	0.104	0.10	0.02
204	415.5	0.0060	0.006	0.091	0.09	0.02
205	415.4	0.0060	0.006	0.091	0.09	0.02
206	415.7	0.0060	0.006	0.091	0.09	0.02
207	440.4	0.0064	0.006	0.101	0.10	0.02
208	440.4	0.0064	0.006	0.101	0.10	0.02
209	440.5	0.0064	0.006	0.101	0.10	0.02

Table A24. Uncertainty analysis of calculated model scale delivered power (U_{PD}), self propulsion test .

Data Spot #	Model Speed V (ft/sec)	Q (in-lbf)	N (RPM)	PD (Hp)	δPD/δQ (Hp/in-lbf)	δPD/δN (Hp-min)	B_Q (in-lbf)	B_N (RPM)	B_{PD} (Hp)	P_Q (in-lbf)	P_N (RPM)	P_{PD} (Hp)	U_{PD} (Hp)	U_{PD} (%)
128	4.019	10.642	281.3	0.047	0.0045	0.0002	0.100	0.004	0.0004	0.070	0.037	0.0003	0.0005	1.14
129	4.020	10.624	281.3	0.047	0.0045	0.0002	0.100	0.004	0.0004	0.070	0.037	0.0003	0.0005	1.15
130	6.017	22.835	417.5	0.151	0.0066	0.0004	0.100	0.006	0.0007	0.122	0.092	0.0008	0.0010	0.69
131	6.017	22.812	417.5	0.151	0.0066	0.0004	0.100	0.006	0.0007	0.122	0.092	0.0008	0.0010	0.69
132	6.017	22.831	417.5	0.151	0.0066	0.0004	0.100	0.006	0.0007	0.122	0.092	0.0008	0.0010	0.69
133	4.378	12.016	303.8	0.058	0.0048	0.0002	0.100	0.004	0.0005	0.076	0.046	0.0004	0.0006	1.04
134	4.378	12.013	303.8	0.058	0.0048	0.0002	0.100	0.004	0.0005	0.076	0.046	0.0004	0.0006	1.04
135	4.378	12.038	303.8	0.058	0.0048	0.0002	0.100	0.004	0.0005	0.076	0.046	0.0004	0.0006	1.04
136	4.378	12.111	303.8	0.058	0.0048	0.0002	0.100	0.004	0.0005	0.076	0.046	0.0004	0.0006	1.04
137	4.376	12.089	303.8	0.058	0.0048	0.0002	0.100	0.004	0.0005	0.076	0.046	0.0004	0.0006	1.04
138	4.376	12.087	303.8	0.058	0.0048	0.0002	0.100	0.004	0.0005	0.076	0.046	0.0004	0.0006	1.04
139	4.378	12.087	303.8	0.058	0.0048	0.0002	0.100	0.004	0.0005	0.076	0.046	0.0004	0.0006	1.04
140	4.378	12.072	303.8	0.058	0.0048	0.0002	0.100	0.004	0.0005	0.076	0.046	0.0004	0.0006	1.04
141	4.378	12.039	303.8	0.058	0.0048	0.0002	0.100	0.004	0.0005	0.076	0.046	0.0004	0.0006	1.04
142	4.378	12.112	303.8	0.058	0.0048	0.0002	0.100	0.004	0.0005	0.076	0.046	0.0004	0.0006	1.04
143	4.378	12.108	303.8	0.058	0.0048	0.0002	0.100	0.004	0.0005	0.076	0.046	0.0004	0.0006	1.04
144	4.378	12.087	303.8	0.058	0.0048	0.0002	0.100	0.004	0.0005	0.076	0.046	0.0004	0.0006	1.04
145	4.378	12.093	303.8	0.058	0.0048	0.0002	0.100	0.004	0.0005	0.076	0.046	0.0004	0.0006	1.04
146	4.378	12.094	303.8	0.058	0.0048	0.0002	0.100	0.004	0.0005	0.076	0.046	0.0004	0.0006	1.04
147	4.378	12.073	303.8	0.058	0.0048	0.0002	0.100	0.004	0.0005	0.076	0.046	0.0004	0.0006	1.04
148	4.380	12.096	303.8	0.058	0.0048	0.0002	0.100	0.004	0.0005	0.076	0.046	0.0004	0.0006	1.04
149	4.378	12.083	303.7	0.058	0.0048	0.0002	0.100	0.004	0.0005	0.076	0.046	0.0004	0.0006	1.04
150	4.380	12.162	303.8	0.059	0.0048	0.0002	0.100	0.004	0.0005	0.076	0.046	0.0004	0.0006	1.03
151	4.378	12.107	303.8	0.058	0.0048	0.0002	0.100	0.004	0.0005	0.076	0.046	0.0004	0.0006	1.04
152	4.378	12.089	303.8	0.058	0.0048	0.0002	0.100	0.004	0.0005	0.076	0.046	0.0004	0.0006	1.04
153	3.377	7.464	234.9	0.028	0.0037	0.0001	0.100	0.003	0.0004	0.056	0.019	0.0002	0.0004	1.53
154	3.381	7.383	234.5	0.027	0.0037	0.0001	0.100	0.003	0.0004	0.056	0.019	0.0002	0.0004	1.55
155	3.384	7.330	234.1	0.027	0.0037	0.0001	0.100	0.003	0.0004	0.055	0.018	0.0002	0.0004	1.56
156	5.014	16.010	348.3	0.088	0.0055	0.0003	0.100	0.005	0.0006	0.093	0.064	0.0005	0.0008	0.85
157	5.016	16.033	348.3	0.089	0.0055	0.0003	0.100	0.005	0.0006	0.093	0.064	0.0005	0.0008	0.85
158	5.016	16.014	348.3	0.088	0.0055	0.0003	0.100	0.005	0.0006	0.093	0.064	0.0005	0.0008	0.85
159	5.706	20.016	394.2	0.125	0.0063	0.0003	0.100	0.006	0.0006	0.110	0.082	0.0007	0.0009	0.74
160	5.706	20.053	394.2	0.125	0.0063	0.0003	0.100	0.006	0.0006	0.110	0.082	0.0007	0.0009	0.74
161	5.705	19.985	394.2	0.125	0.0063	0.0003	0.100	0.006	0.0006	0.110	0.082	0.0007	0.0009	0.75
162	5.705	20.048	394.2	0.125	0.0063	0.0003	0.100	0.006	0.0006	0.110	0.082	0.0007	0.0009	0.74
163	5.705	20.066	394.2	0.126	0.0063	0.0003	0.100	0.006	0.0006	0.110	0.082	0.0007	0.0009	0.74
164	5.705	20.118	394.2	0.126	0.0063	0.0003	0.100	0.006	0.0006	0.111	0.082	0.0007	0.0009	0.74
165	5.705	20.134	394.2	0.126	0.0063	0.0003	0.100	0.006	0.0006	0.111	0.082	0.0007	0.0009	0.74
166	5.703	20.117	394.2	0.126	0.0063	0.0003	0.100	0.006	0.0006	0.111	0.082	0.0007	0.0009	0.74
167	5.703	20.152	394.3	0.126	0.0063	0.0003	0.100	0.006	0.0006	0.111	0.082	0.0007	0.0009	0.74
168	5.705	20.142	394.2	0.126	0.0063	0.0003	0.100	0.006	0.0006	0.111	0.082	0.0007	0.0009	0.74
169	5.705	20.142	394.2	0.126	0.0063	0.0003	0.100	0.006	0.0006	0.111	0.082	0.0007	0.0009	0.74

Table A24. Uncertainty analysis of calculated model scale delivered power (U_{PD}), self propulsion test, continued.

Data Spot #	Model Speed V (ft/sec)	Q (in-lbf)	N (RPM)	PD (Hp)	δPD/δQ (Hp/in-lbf)	δPD/δN (Hp-min)	B_Q (in-lbf)	B_N (RPM)	B_{PD} (Hp)	P_Q (in-lbf)	P_N (RPM)	P_{PD} (Hp)	U_{PD} (Hp)	U_{PD} (%)
170	5.705	20.117	394.2	0.126	0.0063	0.0003	0.100	0.006	0.0006	0.111	0.082	0.0007	0.0009	0.74
171	5.705	20.131	394.1	0.126	0.0063	0.0003	0.100	0.006	0.0006	0.111	0.082	0.0007	0.0009	0.74
172	5.701	20.157	394.2	0.126	0.0063	0.0003	0.100	0.006	0.0006	0.111	0.082	0.0007	0.0009	0.74
173	5.703	20.147	394.2	0.126	0.0063	0.0003	0.100	0.006	0.0006	0.111	0.082	0.0007	0.0009	0.74
174	3.691	8.717	255.4	0.035	0.0041	0.0001	0.100	0.004	0.0004	0.061	0.027	0.0002	0.0005	1.34
175	3.691	8.711	255.4	0.035	0.0041	0.0001	0.100	0.004	0.0004	0.061	0.027	0.0002	0.0005	1.35
176	5.344	18.039	370.4	0.106	0.0059	0.0003	0.100	0.005	0.0006	0.102	0.073	0.0006	0.0008	0.79
177	5.344	18.067	370.4	0.106	0.0059	0.0003	0.100	0.005	0.0006	0.102	0.073	0.0006	0.0008	0.79
178	5.344	18.112	370.4	0.106	0.0059	0.0003	0.100	0.005	0.0006	0.102	0.073	0.0006	0.0008	0.79
179	7.674	48.645	588.4	0.454	0.0093	0.0008	0.103	0.008	0.0010	0.234	0.160	0.0022	0.0024	0.53
180	7.679	48.551	588.4	0.453	0.0093	0.0008	0.103	0.008	0.0010	0.234	0.160	0.0022	0.0024	0.53
181	**6.692**	**28.497**	**469.7**	**0.212**	**0.0075**	**0.0005**	**0.101**	**0.007**	**0.0008**	**0.147**	**0.112**	**0.0011**	**0.0014**	**0.66**
182	6.692	28.601	469.6	0.213	0.0075	0.0005	0.101	0.007	0.0008	0.147	0.112	0.0011	0.0013	0.62
183	6.692	28.570	469.7	0.213	0.0075	0.0005	0.101	0.007	0.0008	0.147	0.112	0.0011	0.0013	0.63
184	6.694	28.646	469.7	0.213	0.0075	0.0005	0.101	0.007	0.0008	0.148	0.112	0.0011	0.0013	0.62
185	6.696	28.623	469.7	0.213	0.0075	0.0005	0.101	0.007	0.0008	0.147	0.112	0.0011	0.0013	0.62
186	6.694	28.702	469.6	0.214	0.0075	0.0005	0.101	0.007	0.0008	0.148	0.112	0.0011	0.0013	0.62
187	6.692	28.754	469.7	0.214	0.0075	0.0005	0.101	0.007	0.0008	0.148	0.112	0.0011	0.0013	0.62
188	6.692	28.610	469.7	0.213	0.0075	0.0005	0.101	0.007	0.0008	0.147	0.112	0.0011	0.0013	0.62
189	6.692	28.628	469.6	0.213	0.0075	0.0005	0.101	0.007	0.0008	0.148	0.112	0.0011	0.0013	0.62
190	6.694	28.628	469.6	0.213	0.0075	0.0005	0.101	0.007	0.0008	0.148	0.112	0.0011	0.0013	0.62
191	6.696	28.593	469.6	0.213	0.0075	0.0005	0.101	0.007	0.0008	0.147	0.112	0.0011	0.0013	0.62
192	6.692	28.651	469.6	0.213	0.0075	0.0005	0.101	0.007	0.0008	0.148	0.112	0.0011	0.0013	0.62
193	6.694	28.532	469.6	0.213	0.0075	0.0005	0.101	0.007	0.0008	0.147	0.112	0.0011	0.0013	0.63
194	7.013	32.383	496.5	0.255	0.0079	0.0005	0.101	0.007	0.0008	0.164	0.123	0.0013	0.0015	0.59
195	7.014	32.422	496.4	0.255	0.0079	0.0005	0.101	0.007	0.0008	0.164	0.123	0.0013	0.0015	0.59
196	7.013	32.422	496.4	0.255	0.0079	0.0005	0.101	0.007	0.0008	0.164	0.123	0.0013	0.0015	0.59
197	7.344	38.824	536.1	0.330	0.0085	0.0006	0.102	0.008	0.0009	0.192	0.139	0.0016	0.0018	0.56
198	7.345	38.574	535.2	0.328	0.0085	0.0006	0.102	0.008	0.0009	0.191	0.139	0.0016	0.0018	0.56
199	4.685	14.101	326.0	0.073	0.0052	0.0002	0.100	0.005	0.0005	0.085	0.055	0.0004	0.0007	0.93
200	4.687	14.042	326.0	0.073	0.0052	0.0002	0.100	0.005	0.0005	0.084	0.055	0.0004	0.0007	0.93
201	4.687	14.058	326.0	0.073	0.0052	0.0002	0.100	0.005	0.0005	0.084	0.055	0.0004	0.0007	0.93
202	6.344	26.557	448.1	0.189	0.0071	0.0004	0.101	0.006	0.0007	0.139	0.104	0.0010	0.0012	0.65
203	6.344	26.554	448.1	0.189	0.0071	0.0004	0.101	0.006	0.0007	0.139	0.104	0.0010	0.0012	0.65
204	6.020	22.524	415.5	0.148	0.0066	0.0004	0.100	0.006	0.0007	0.121	0.091	0.0008	0.0010	0.70
205	6.019	22.537	415.4	0.149	0.0066	0.0004	0.100	0.006	0.0007	0.121	0.091	0.0008	0.0010	0.70
206	6.020	22.521	415.7	0.149	0.0066	0.0004	0.100	0.006	0.0007	0.121	0.091	0.0008	0.0010	0.70
207	6.344	25.284	440.4	0.177	0.0070	0.0004	0.101	0.006	0.0007	0.133	0.101	0.0009	0.0012	0.66
208	6.344	25.355	440.4	0.177	0.0070	0.0004	0.101	0.006	0.0007	0.133	0.101	0.0009	0.0012	0.66
209	6.346	25.480	440.5	0.178	0.0070	0.0004	0.101	0.006	0.0007	0.134	0.101	0.0009	0.0012	0.66

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APPENDIX B

INSTRUMENTATION CALIBRATION DATA AND CALCULATIONS

APPENDIX B - INSTRUMENTATION CALIBRATION DATA AND CALCULATIONS

FIGURES

TABLES

Table B1. Calibration Standard bias limit (Bstd) for the block gage used to measure model total resistance (R_T), resistance test.

i = 1,N	Total Weight Applied, Wstd (lbf)	Sum (S) of the Squares of the IndividualWeights : S(Wi)^2 (lbf^2)		Square Root of the Sum of Squares of the Individual Weights : (S(Wi)^2)^.5 (lbf)	Bstd for Each Intermediate Sum 0.0001 * (S(Wi)^2)^.5 (lbf)
1	0.000	0 =	0.000	0.000	0.00000
2	5.000	5^2 =	25.000	5.000	0.00050
3	10.000	5^2 +5^2 =	50.000	7.071	0.00071
4	15.000	5^2 +5^2 +5^2 =	75.000	8.660	0.00087
5	20.000	5^2 +5^2 +5^2 +5^2 =	100.000	10.000	0.00100
6	25.000	5^2 +5^2 +5^2 +5^2 +5^2 =	125.000	11.180	0.00112
7	30.000	5^2 +5^2 +5^2 +5^2 +5^2 +5^2 =	150.000	12.247	0.00122
8	35.000	5^2 +5^2 +5^2 +5^2 +5^2 +5^2 +5^2 =	175.000	13.229	0.00132
9	30.000	5^2 +5^2 +5^2 +5^2 +5^2 +5^2 =	150.000	12.247	0.00122
10	25.000	5^2 +5^2 +5^2 +5^2 +5^2 =	125.000	11.180	0.00112
11	20.000	5^2 +5^2 +5^2 +5^2 =	100.000	10.000	0.00100
12	15.000	5^2 +5^2 +5^2 =	75.000	8.660	0.00087
13	10.000	5^2 +5^2 =	50.000	7.071	0.00071
14	5.000	5^2 =	25.000	5.000	0.00050
15	0.000	0 =	0.000	0.000	0.00000
16	0.000	0 =	0.000	0.000	0.00000
17	5.000	5^2 =	25.000	5.000	0.00050
18	10.000	5^2 +5^2 =	50.000	7.071	0.00071
19	15.000	5^2 +5^2 +5^2 =	75.000	8.660	0.00087
20	20.000	5^2 +5^2 +5^2 +5^2 =	100.000	10.000	0.00100
21	25.000	5^2 +5^2 +5^2 +5^2 +5^2 =	125.000	11.180	0.00112
22	30.000	5^2 +5^2 +5^2 +5^2 +5^2 +5^2 =	150.000	12.247	0.00122
23	35.000	5^2 +5^2 +5^2 +5^2 +5^2 +5^2 +5^2 =	175.000	13.229	0.00132
24	30.000	5^2 +5^2 +5^2 +5^2 +5^2 +5^2 =	150.000	12.247	0.00122
25	25.000	5^2 +5^2 +5^2 +5^2 +5^2 =	125.000	11.180	0.00112
26	20.000	5^2 +5^2 +5^2 +5^2 =	100.000	10.000	0.00100
27	15.000	5^2 +5^2 +5^2 =	75.000	8.660	0.00087
28	10.000	5^2 +5^2 =	50.000	7.071	0.00071
29	5.000	5^2 =	25.000	5.000	0.00050
30	0.000	0 =	0.000	0.000	0.00000
31	0.000	0 =	0.000	0.000	0.00000
32	5.000	5^2 =	25.000	5.000	0.00050
33	10.000	5^2 +5^2 =	50.000	7.071	0.00071
34	15.000	5^2 +5^2 +5^2 + =	75.000	8.660	0.00087
35	20.000	5^2 +5^2 +5^2 +5^2 =	100.000	10.000	0.00100
36	25.000	5^2 +5^2 +5^2 +5^2 +5^2 =	125.000	11.180	0.00112
37	30.000	5^2 +5^2 +5^2 +5^2 +5^2 +5^2 =	150.000	12.247	0.00122
38	35.000	5^2 +5^2 +5^2 +5^2 +5^2 +5^2 +5^2 =	175.000	13.229	0.00132
39	30.000	5^2 +5^2 +5^2 +5^2 +5^2 +5^2 =	150.000	12.247	0.00122
40	25.000	5^2 +5^2 +5^2 +5^2 +5^2 =	125.000	11.180	0.00112
41	20.000	5^2 +5^2 +5^2 +5^2 =	100.000	10.000	0.00100
42	15.000	5^2 +5^2 +5^2 =	75.000	8.660	0.00087
43	10.000	5^2 +5^2 =	50.000	7.071	0.00071
44	5.000	5^2 =	25.000	5.000	0.00050
45	0.000	0 =	0.000	0.000	0.00000

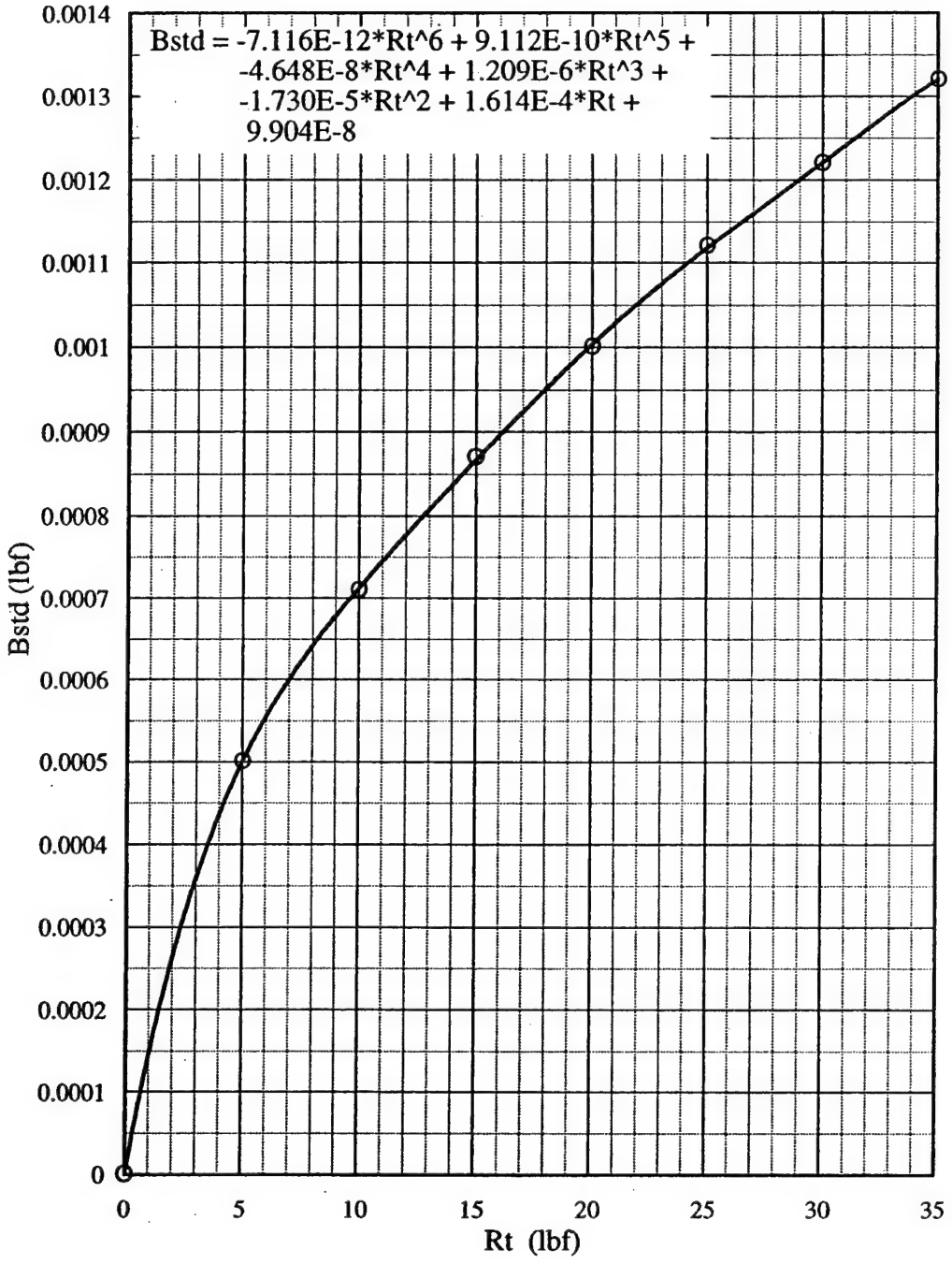

Fig. B1. Calibration Standard bias limit (Bstd) for the block gage used to measure model total resistance (R_T), resistance test.

Table B2. Standard error of estimate (SEE) and calibration curvefit bias (Bcf) for the block gage used to measure model total resistance (R_T), resistance test.

i = 1,N	Weight Applied Fi (lbf)	Voltage Measured Ei (volts)	Intermediate Cal Cst Ci =Fi/Ei (lbf/volt)	[Fi-(C*Ei)]^2
1	5.000	-0.732	-6.8299	1.664E-05
2	10.000	-1.464	-6.8324	6.657E-05
3	15.000	-2.195	-6.8353	2.919E-05
4	20.000	-2.926	-6.8363	7.002E-06
5	25.000	-3.655	-6.8391	1.900E-04
6	30.000	-4.384	-6.8430	9.127E-04
7	35.000	-5.108	-6.8523	6.532E-03
8	30.000	-4.385	-6.8422	5.464E-04
9	25.000	-3.657	-6.8365	1.218E-08
10	20.000	-2.927	-6.8332	8.991E-05
11	15.000	-2.196	-6.8299	1.498E-04
12	10.000	-1.465	-6.8252	2.249E-04
13	5.000	-0.733	-6.8223	1.192E-04
14	5.000	-0.731	-6.8369	7.599E-06
15	10.000	-1.463	-6.8356	1.751E-06
16	15.000	-2.193	-6.8391	6.839E-05
17	20.000	-2.924	-6.8389	1.216E-04
18	25.000	-3.655	-6.8403	1.900E-04
19	30.000	-4.384	-6.8432	9.127E-04
20	35.000	-5.109	-6.8511	5.474E-03
21	30.000	-4.385	-6.8411	5.464E-04
22	25.000	-3.657	-6.8369	1.218E-08
23	20.000	-2.927	-6.8335	8.991E-05
24	15.000	-2.196	-6.8322	1.498E-04
25	10.000	-1.464	-6.8312	6.657E-05
26	5.000	-0.732	-6.8271	1.664E-05
27	5.000	-0.731	-6.8354	7.599E-06
28	10.000	-1.463	-6.8350	1.751E-06
29	15.000	-2.193	-6.8387	6.839E-05
30	20.000	-2.924	-6.8397	1.216E-04
31	25.000	-3.655	-6.8409	1.900E-04
32	30.000	-4.383	-6.8442	1.373E-03
33	35.000	-5.107	-6.8540	7.684E-03
34	30.000	-4.384	-6.8428	9.127E-04
35	25.000	-3.657	-6.8370	1.218E-08
36	20.000	-2.927	-6.8330	8.991E-05
37	15.000	-2.196	-6.8291	1.498E-04
38	10.000	-1.466	-6.8225	4.766E-04
39	5.000	-0.734	-6.8138	3.151E-04

N = 39 , N-2 = 37		
Avg. Calibration Factor (lbf/volt) = C =	-6.8362	
Sum = sum of the terms [Fi-(C*Ei)]^2 =		0.0279
SEE (lbf) = [Sum / N-2]^0.5 =		0.0275
Bcf (lbf)= 2SEE =		0.0550

Table B3. Calibration Standard bias limit (Bstd) for the block gage used to measure model tow force (Fd), self propulsion test.

i = 1,N	Total Weight Applied, Wstd (lbf)	Sum (S) of the Squares of the Individual Weights : S(Wi)^2 (lbf^2)		Square Root of the Sum of Squares of the Individual Weights : (S(Wi)^2)^.5 (lbf)	Bstd for Each Intermediate Sum 0.0001 * (S(Wi)^2)^.5 (lbf)
1	0.000	0 =	0.000	0.000	0.00000
2	1.000	1^2 =	1.000	1.000	0.00010
3	2.000	1^2 +1^2 =	2.000	1.414	0.00014
4	3.000	1^2 +1^2+1^2 =	3.000	1.732	0.00017
5	4.000	1^2 +1^2+1^2+1^2 =	4.000	2.000	0.00020
6	5.000	1^2 +1^2+1^2+1^2+1^2 =	5.000	2.236	0.00022
7	6.000	1^2 +1^2+1^2+1^2+1^2+1^2 =	6.000	2.449	0.00024
8	5.000	1^2 +1^2+1^2+1^2+1^2 =	5.000	2.236	0.00022
9	4.000	1^2 +1^2+1^2+1^2 =	4.000	2.000	0.00020
10	3.000	1^2 +1^2+1^2 =	3.000	1.732	0.00017
11	2.000	1^2 +1^2 =	2.000	1.414	0.00014
12	1.000	1^2 =	1.000	1.000	0.00010
13	0.000	0 =	0.000	0.000	0.00000
14	0.000	0 =	0.000	0.000	0.00000
15	1.000	1^2 =	1.000	1.000	0.00010
16	2.000	1^2 +1^2 =	2.000	1.414	0.00014
17	3.000	1^2 +1^2+1^2 =	3.000	1.732	0.00017
18	4.000	1^2 +1^2+1^2+1^2 =	4.000	2.000	0.00020
19	5.000	1^2 +1^2+1^2+1^2+1^2 =	5.000	2.236	0.00022
20	6.000	1^2 +1^2+1^2+1^2+1^2+1^2 =	6.000	2.449	0.00024
21	5.000	1^2 +1^2+1^2+1^2+1^2 =	5.000	2.236	0.00022
22	4.000	1^2 +1^2+1^2+1^2 =	4.000	2.000	0.00020
23	3.000	1^2 +1^2+1^2 =	3.000	1.732	0.00017
24	2.000	1^2 +1^2 =	2.000	1.414	0.00014
25	1.000	1^2 =	1.000	1.000	0.00010
26	0.000	0 =	0.000	0.000	0.00000
27	0.000	0 =	0.000	0.000	0.00000
28	1.000	1^2 =	1.000	1.000	0.00010
29	2.000	1^2 +1^2 =	2.000	1.414	0.00014
30	3.000	1^2 +1^2+1^2 =	3.000	1.732	0.00017
31	4.000	1^2 +1^2+1^2+1^2 =	4.000	2.000	0.00020
32	5.000	1^2 +1^2+1^2+1^2+1^2 =	5.000	2.236	0.00022
33	6.000	1^2 +1^2+1^2+1^2+1^2+1^2 =	6.000	2.449	0.00024
34	5.000	1^2 +1^2+1^2+1^2+1^2 =	5.000	2.236	0.00022
35	4.000	1^2 +1^2+1^2+1^2 =	4.000	2.000	0.00020
36	3.000	1^2 +1^2+1^2 =	3.000	1.732	0.00017
37	2.000	1^2 +1^2 =	2.000	1.414	0.00014
38	1.000	1^2 =	1.000	1.000	0.00010
39	0.000	0 =	0.000	0.000	0.00000

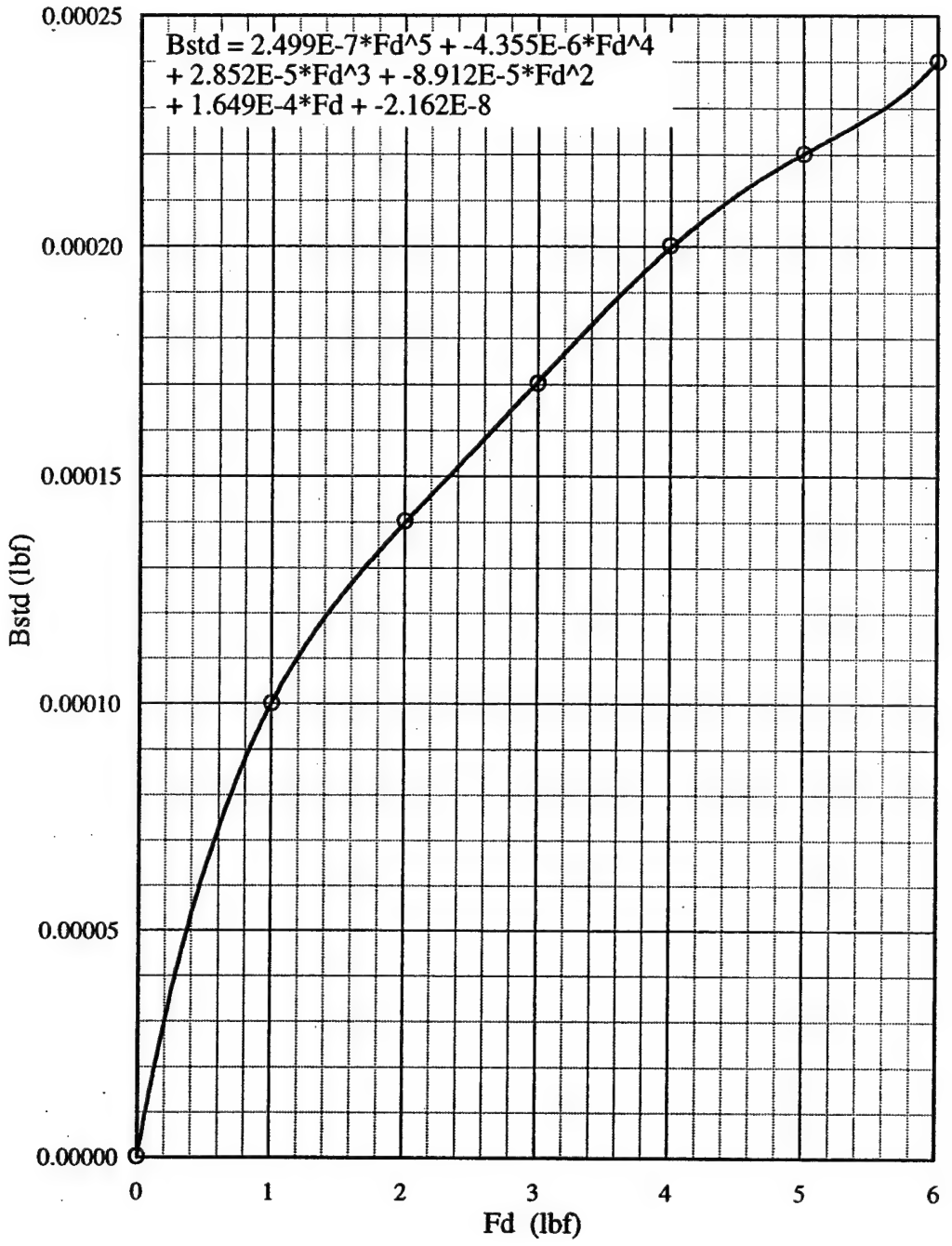

Fig. B2. Calibration Standard bias limit (Bstd) for the block gage used to measure model tow force (Fd), self propulsion test.

Table B4. Standard error of estimate (SEE) and calibration curvefit bias (Bcf) for the block gage used to measure model tow force (Fd), self propulsion test.

i = 1,N	Weight Applied Fi (lbf)	Voltage Measured Ei (volts)	Intermediate Cal Cst Ci =Fi/Ei (lbf/volt)	[Fi-(C*Ei)]^2
1	1.000	-0.146	-6.8382	1.535E-08
2	2.000	-0.292	-6.8581	6.140E-08
3	3.000	-0.438	-6.8519	1.381E-07
4	4.000	-0.584	-6.8490	2.456E-07
5	5.000	-0.730	-6.8472	3.837E-07
6	6.000	-0.877	-6.8450	5.766E-05
7	5.000	-0.730	-6.8457	3.837E-07
8	4.000	-0.584	-6.8493	2.456E-07
9	3.000	-0.438	-6.8528	1.381E-07
10	2.000	-0.291	-6.8617	4.359E-05
11	1.000	-0.146	-6.8470	1.535E-08
12	1.000	-0.146	-6.8458	1.535E-08
13	2.000	-0.291	-6.8625	4.359E-05
14	3.000	-0.438	-6.8554	1.381E-07
15	4.000	-0.584	-6.8489	2.456E-07
16	5.000	-0.730	-6.8480	3.837E-07
17	6.000	-0.876	-6.8492	5.526E-07
18	5.000	-0.730	-6.8480	3.837E-07
19	4.000	-0.584	-6.8470	2.456E-07
20	3.000	-0.438	-6.8487	1.381E-07
21	2.000	-0.292	-6.8599	6.140E-08
22	1.000	-0.146	-6.8534	1.535E-08
23	1.000	-0.146	-6.8487	1.535E-08
24	2.000	-0.291	-6.8640	4.359E-05
25	3.000	-0.437	-6.8579	4.197E-05
26	4.000	-0.584	-6.8505	2.456E-07
27	5.000	-0.730	-6.8474	3.837E-07
28	6.000	-0.876	-6.8455	5.526E-07
29	5.000	-0.730	-6.8464	3.837E-07
30	4.000	-0.584	-6.8448	2.456E-07
31	3.000	-0.438	-6.8485	1.381E-07
32	2.000	-0.292	-6.8537	6.140E-08
33	1.000	-0.146	-6.8353	1.535E-08

N = 33 , N-2 = 31		
Avg. Calibration Factor (lbf/volt) = C =	-6.8502	
Sum = sum of the terms [Fi-(C*Ei)]^2 =		0.0002
SEE (lbf) = [Sum / N-2]^0.5 =		0.0028
Bcf (lbf)= 2SEE =		0.0055

Table B5. Calibration Standard bias limit (Bstd) for the transmission dynamometer used to measure model propeller shaft thrust (T), self propulsion test.

i = 1,N	Total Thrust Applied, **Tstd** : (lbf)	Total Weight Applied, ΣWi : (lbf)	Total Weight^2 Σ(Wi^2) : (lbf^2)	**Bstd** for Each Intermediate Quantity (lbf)
1	0.0	0.0	0.0	0.00000
2	6.0	2.0	4.0	0.01261
3	12.0	4.0	8.0	0.02521
4	18.0	6.0	12.0	0.03781
5	24.0	8.0	16.0	0.05041
6	30.0	10.0	20.0	0.06301
7	36.0	12.0	24.0	0.07561
8	30.0	10.0	20.0	0.06301
9	24.0	8.0	16.0	0.05041
10	18.0	6.0	12.0	0.03781
11	12.0	4.0	8.0	0.02521
12	6.0	2.0	4.0	0.01261
13	0.0	0.0	0.0	0.00000
14	0.0	0.0	0.0	0.00000
15	6.0	2.0	4.0	0.01261
16	12.0	4.0	8.0	0.02521
17	18.0	6.0	12.0	0.03781
18	24.0	8.0	16.0	0.05041
19	30.0	10.0	20.0	0.06301
20	36.0	12.0	24.0	0.07561
21	30.0	10.0	20.0	0.06301
22	24.0	8.0	16.0	0.05041
23	18.0	6.0	12.0	0.03781
24	12.0	4.0	8.0	0.02521
25	6.0	2.0	4.0	0.01261
26	0.0	0.0	0.0	0.00000
27	0.0	0.0	0.0	0.00000
28	6.0	2.0	4.0	0.01261
29	12.0	4.0	8.0	0.02521
30	18.0	6.0	12.0	0.03781
31	24.0	8.0	16.0	0.05041
32	30.0	10.0	20.0	0.06301
33	36.0	12.0	24.0	0.07561
34	30.0	10.0	20.0	0.06301
35	24.0	8.0	16.0	0.05041
36	18.0	6.0	12.0	0.03781
37	12.0	4.0	8.0	0.02521
38	6.0	2.0	4.0	0.01261
39	0.0	0.0	0.0	0.00000

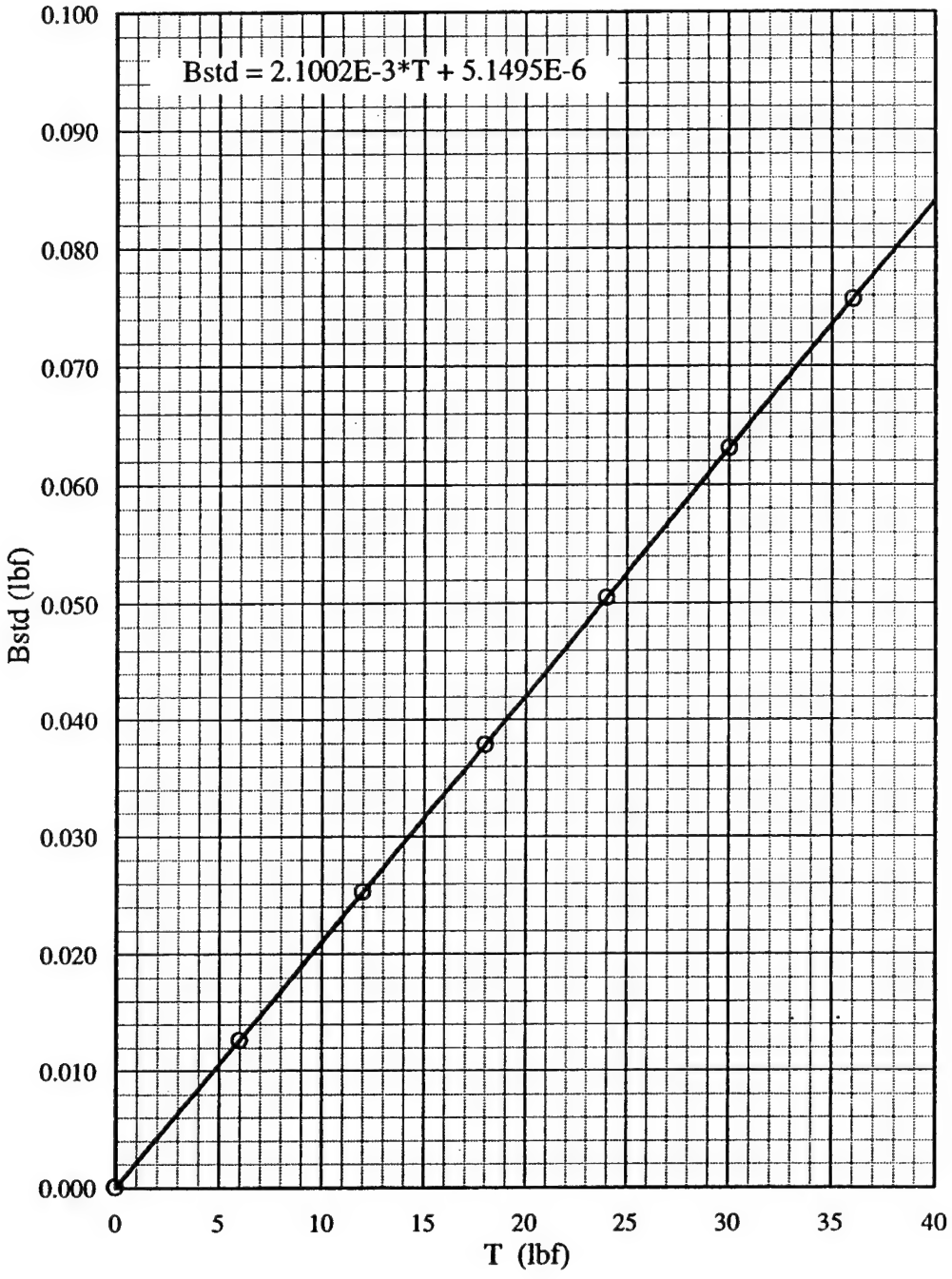

Fig. B3. Calibration Standard bias limit (Bstd) for the transmission dynamometer used to measure model propeller shaft thrust (T), self propulsion test.

Table B6. Standard error of estimate (SEE) and calibration curvefit bias (Bcf) for the transmission dynamometer used to measure model propeller shaft thrust (T), self propulsion test.

i = 1,N	Force Applied Fi (lbf)	Voltage Measured Ei (volts)	Intermediate Cal Cst Ci =Fi/Ei (lbf/volt)	[Fi-(C*Ei)]^2
1	6.000	1.109	5.4097	1.595E-05
2	12.000	2.219	5.4070	6.655E-06
3	18.000	3.328	5.4086	4.320E-05
4	24.000	4.439	5.4072	6.108E-08
5	30.000	5.547	5.4079	8.377E-05
6	36.000	6.649	5.4147	2.600E-03
7	30.000	5.546	5.4093	2.120E-04
8	24.000	4.439	5.4072	6.108E-08
9	18.000	3.331	5.4036	9.307E-05
10	12.000	2.221	5.4022	6.779E-05
11	6.000	1.111	5.4019	4.651E-05
12	6.000	1.109	5.4115	1.595E-05
13	12.000	2.220	5.4052	7.991E-06
14	18.000	3.330	5.4058	1.798E-05
15	24.000	4.439	5.4071	6.108E-08
16	30.000	5.549	5.4068	2.758E-06
17	36.000	6.650	5.4134	2.078E-03
18	30.000	5.550	5.4059	4.995E-05
19	24.000	4.442	5.4033	2.712E-04
20	18.000	3.330	5.4049	1.798E-05
21	12.000	2.221	5.4026	6.779E-05
22	6.000	1.110	5.4038	1.998E-06
23	6.000	1.110	5.4051	1.998E-06
24	12.000	2.220	5.4053	7.991E-06
25	18.000	3.329	5.4064	1.360E-06
26	24.000	4.440	5.4049	3.197E-05
27	30.000	5.548	5.4072	1.403E-05
28	36.000	6.648	5.4149	3.181E-03
29	30.000	5.547	5.4087	8.377E-05
30	24.000	4.441	5.4043	1.223E-04
31	18.000	3.329	5.4067	1.360E-06
32	12.000	2.220	5.4043	7.991E-06
33	6.000	1.110	5.4030	1.998E-06

N = 33 , N-2 = 31		
Avg. Calibration Factor (lbf/volt) = C =	5.4067	
Sum = sum of the terms [Fi-(C*Ei)]^2 =		0.0092
SEE (lbf) = [Sum / N-2]^0.5 =		0.0172
Bcf (lbf)= 2SEE =		0.0344

Table B7. Calibration Standard bias limit (Bstd) for the transmission dynamometer used to measure model propeller shaft torque (Q), self propulsion test.

i = 1,N	Total Torque Applied, **Qstd** : (in-lbf)	Total Weight Applied, ΣWi : (lbf)	Total Weight^2 Σ(Wi^2) : (lbf^2)	**Bstd** for Each Intermediate Quantity (in-lbf)
1	0.00	0.00	0.00	0.00000
2	10.00	1.00	1.00	0.00510
3	20.00	2.00	2.00	0.01010
4	30.00	3.00	3.00	0.01510
5	40.00	4.00	4.00	0.02010
6	50.00	5.00	5.00	0.02510
7	60.00	6.00	6.00	0.03010
8	50.00	5.00	5.00	0.02510
9	40.00	4.00	4.00	0.02010
10	30.00	3.00	3.00	0.01510
11	20.00	2.00	2.00	0.01010
12	10.00	1.00	1.00	0.00510
13	0.00	0.00	0.00	0.00000
14	0.00	0.00	0.00	0.00000
15	10.00	1.00	1.00	0.00510
16	20.00	2.00	2.00	0.01010
17	30.00	3.00	3.00	0.01510
18	40.00	4.00	4.00	0.02010
19	50.00	5.00	5.00	0.02510
20	60.00	6.00	6.00	0.03010
21	50.00	5.00	5.00	0.02510
22	40.00	4.00	4.00	0.02010
23	30.00	3.00	3.00	0.01510
24	20.00	2.00	2.00	0.01010
25	10.00	1.00	1.00	0.00510
26	0.00	0.00	0.00	0.00000
27	0.00	0.00	0.00	0.00000
28	10.00	1.00	1.00	0.00510
29	20.00	2.00	2.00	0.01010
30	30.00	3.00	3.00	0.01510
31	40.00	4.00	4.00	0.02010
32	50.00	5.00	5.00	0.02510
33	60.00	6.00	6.00	0.03010
34	50.00	5.00	5.00	0.02510
35	40.00	4.00	4.00	0.02010
36	30.00	3.00	3.00	0.01510
37	20.00	2.00	2.00	0.01010
38	10.00	1.00	1.00	0.00510
39	0.00	0.00	0.00	0.00000

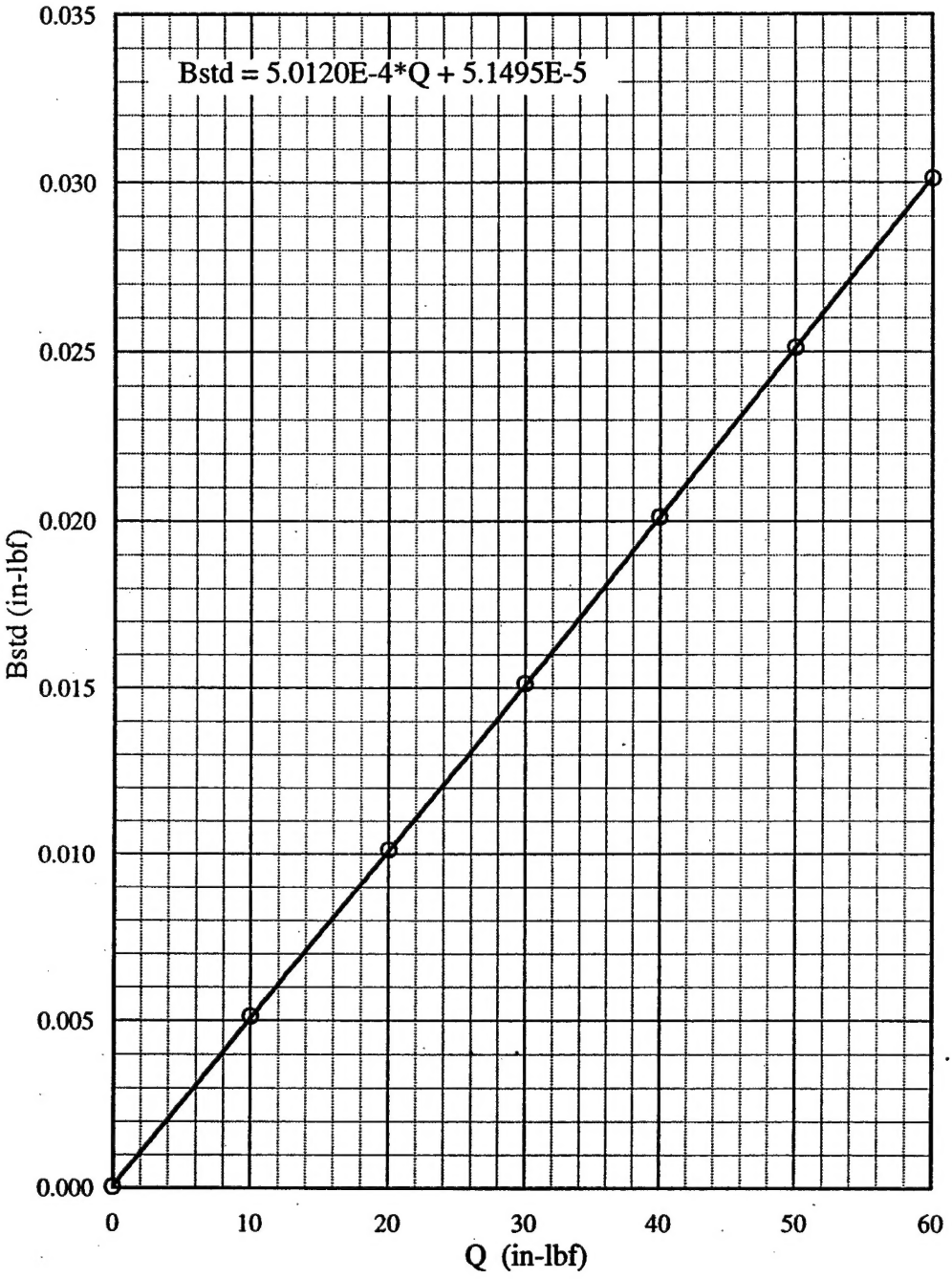

Fig. B4. Calibration Standard bias limit (Bstd) for the transmission dynamometer used to measure model propeller shaft torque (Q), self propulsion test.

Table B8. Standard error of estimate (SEE) and calibration curvefit bias (Bcf) for the transmission dynamometer used to measure model propeller shaft torque (Q), self propulsion test.

i = 1,N	Moment Applied Mi (in-lbf)	Voltage Measured Ei (volts)	Intermediate Cal Cst Ci =Mi/Ei (in-lbf/volt)	[Mi-(C*Ei)]^2
1	10.000	-1.059	-9.4470	9.667E-04
2	20.000	-2.112	-9.4701	2.863E-05
3	30.000	-3.174	-9.4533	4.207E-03
4	40.000	-4.221	-9.4759	3.139E-04
5	50.000	-5.281	-9.4686	5.220E-04
6	60.000	-6.338	-9.4672	1.225E-03
7	50.000	-5.272	-9.4847	3.894E-03
8	40.000	-4.219	-9.4808	1.344E-03
9	30.000	-3.160	-9.4948	4.590E-03
10	20.000	-2.112	-9.4691	2.863E-05
11	10.000	-1.051	-9.5125	1.997E-03
12	10.000	-1.056	-9.4654	7.157E-06
13	20.000	-2.114	-9.4622	5.902E-04
14	30.000	-3.171	-9.4614	1.328E-03
15	40.000	-4.221	-9.4771	3.139E-04
16	50.000	-5.278	-9.4738	3.101E-05
17	60.000	-6.340	-9.4640	2.910E-03
18	50.000	-5.272	-9.4841	3.894E-03
19	40.000	-4.221	-9.4773	3.139E-04
20	30.000	-3.163	-9.4853	1.547E-03
21	20.000	-2.120	-9.4339	6.582E-03
22	10.000	-1.059	-9.4443	9.667E-04
23	10.000	-1.054	-9.4907	2.647E-04
24	20.000	-2.115	-9.4567	1.140E-03
25	30.000	-3.172	-9.4565	2.108E-03
26	40.000	-4.222	-9.4735	6.796E-05
27	50.000	-5.278	-9.4736	3.101E-05
28	60.000	-6.338	-9.4662	1.225E-03
29	50.000	-5.272	-9.4838	3.894E-03
30	40.000	-4.225	-9.4676	4.070E-04
31	30.000	-3.162	-9.4865	2.382E-03
32	20.000	-2.116	-9.4512	1.870E-03
33	10.000	-1.050	-9.5245	2.933E-03

N = 33 , N-2 = 31		
Avg. Calibration Factor (in-lbf/volt) = C =	-9.4722	
Sum = sum of the terms [Mi-(C*Ei)]^2 =		0.0539
SEE (in-lbf) = [Sum / N-2]^0.5 =		0.0417
Bcf (in-lbf)= 2SEE =		0.0834

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